Slag Valorisation Symposium

Science, Innovation & Entrepreneurship in Pursuit of a Sustainable World

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Mechelen, Belgium

Carbonation Workshop

Carbon mineralization: principles, main process routes and product properties

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Topics that we will address

- Carbonation reaction and its applications
- Feedstocks
- Process routes and operating conditions
- Products
- Effects of the process in terms of product properties and CO_2 uptake

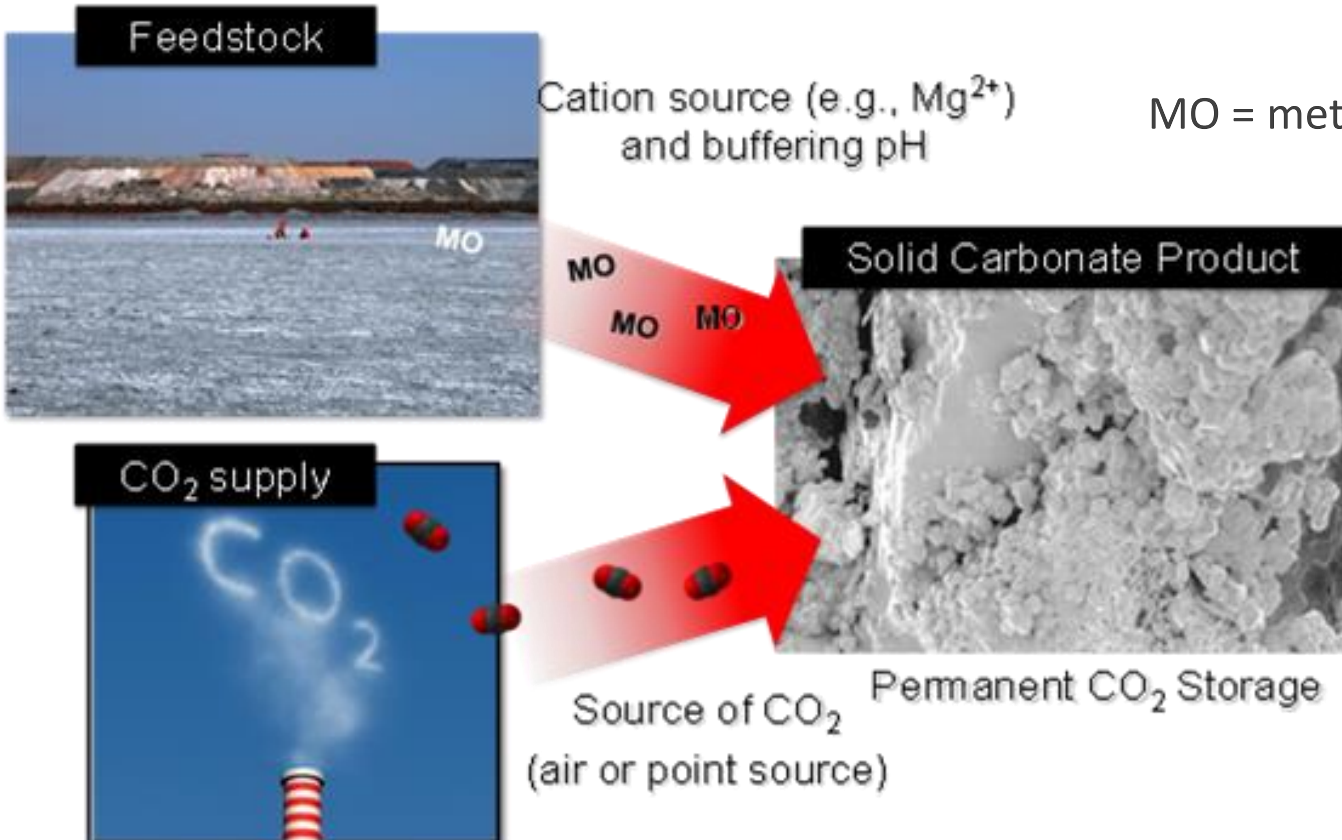
  → leaching behavior

Carbon mineralization: CO_2 conversion to solid carbonates

$$MO + CO_2 \rightarrow MCO_3 + heat$$

M: Calcium, Magnesium (Iron)

MO = metal oxide



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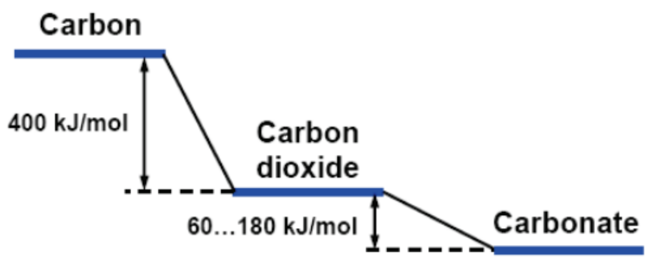
Specific traits of carbonation as a CCUS strategy



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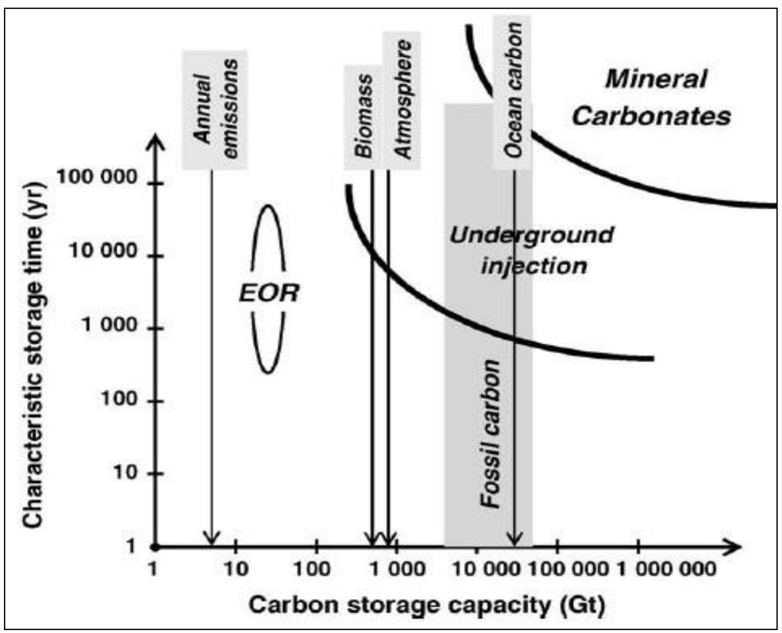
Compared to other CO_2 utilization strategies:

Exothermic reaction



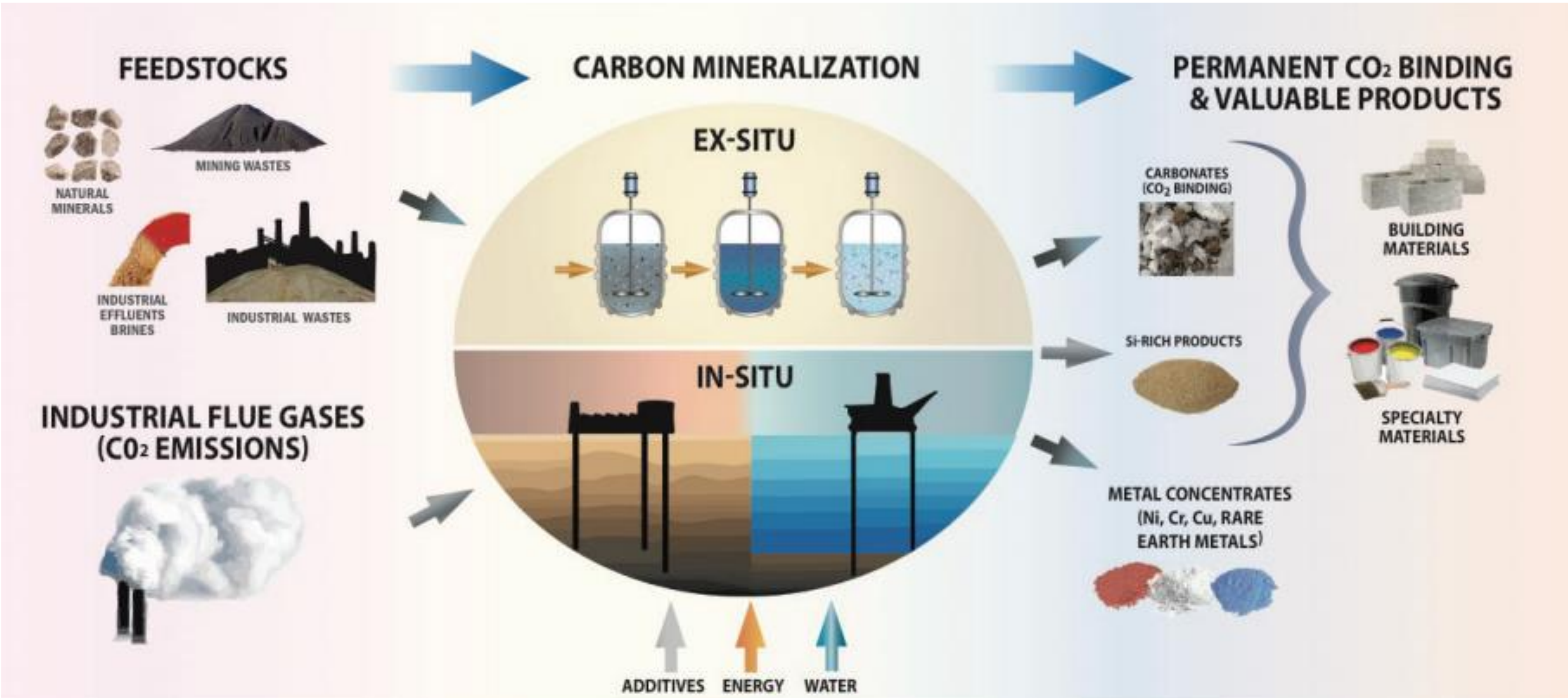
Zevenhoven et al, 2006

Compared to other CO_2 storage strategies:

- *Permanent storage and no need for monitoring*
- *Large capacity (considering minerals)*
- *Possibility of employing waste materials or industrial by-products as feedstocks*
- *Possibility of obtaining a product (and co-products) to use for different applications*

Applications of carbon mineralization

Feedstocks ⟷ **Routes** ⟷ **Products**



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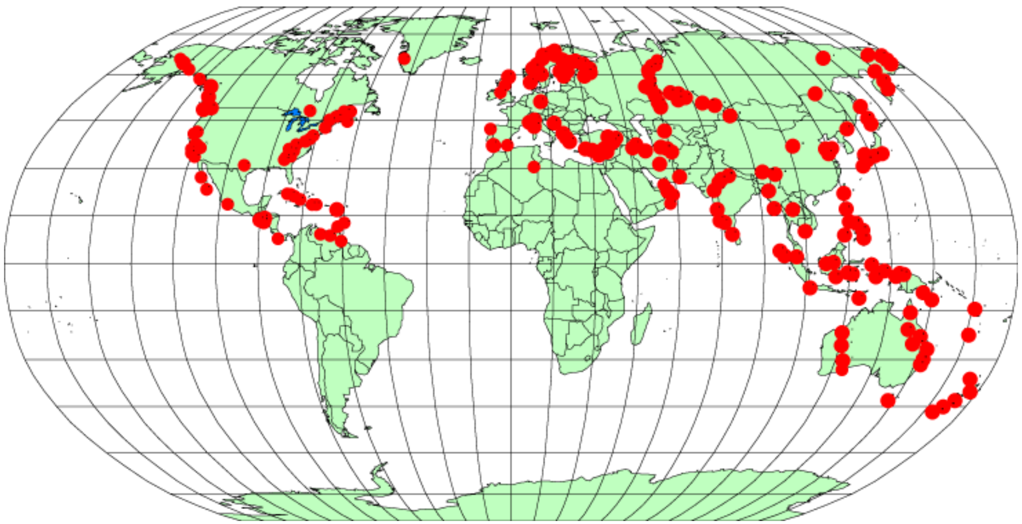
- **Ex situ engineered processes (minerals & industrial residues)**
- In-situ passive weathering (mine tailings)
- Ex situ treatment or curing step (cements/concrete)

Feedstocks for carbon mineralization

- *Ultramaphic rocks : ophiolite belts - Mg silicates*

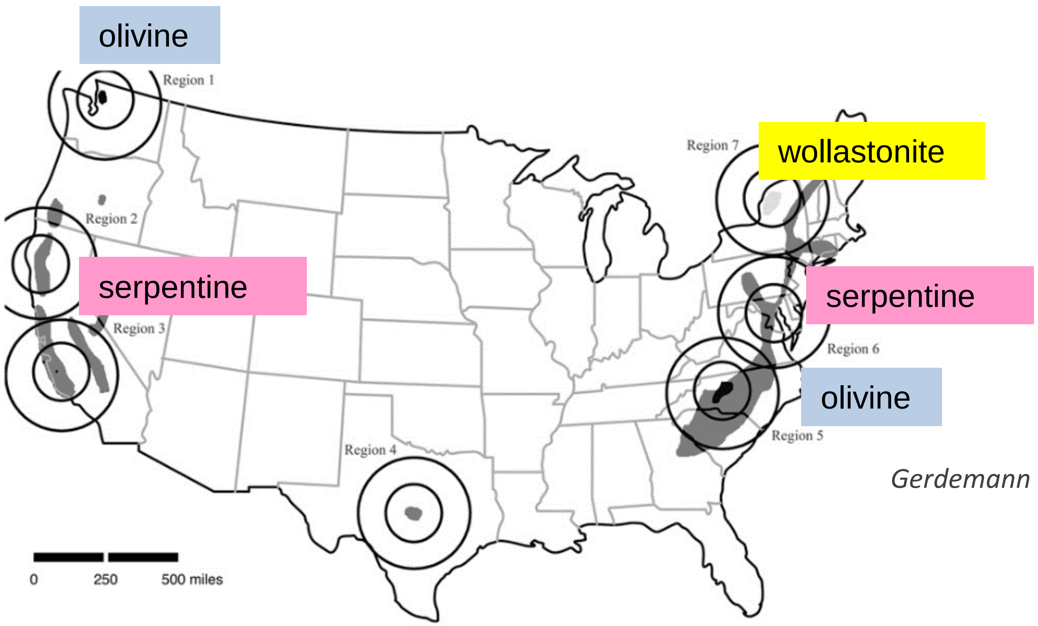


Stoichiometric ratio between tons of rock needed to store 1 ton of CO_2

Rock Type		MgO, wt%	CaO, wt%	R_C	R_{CO_2}
Peridotites	Dunite	49.5	0.3	6.8	1.8
	Harzburgite	45.4	0.7	7.3	2.0
	Lherzolite	28.1	7.3	10.1	2.7
Serpentinite		~40	~0	~8.4	~2.3
Gabbro		~10	~13	~17	~4.7
Basalt	Continental tholeiite	6.2	9.4	26	7.1

Feedstocks for carbon mineralization

- *Silicate minerals*



region	ore mineral and grade
1	olivine, 100%
2–4	serpentine (lizardite), 100%
5	olivine, 70%
6	serpentine (antigorite), 100%
7	wollastonite, 50%

Gerdemann et al, 2007 *Albany Research Center*

Reserves estimated to exceed 2 Gton just in Norway, production 8 Mtons/y

Olivine: $Mg_2SiO_4 + 2CO_2 \leftrightarrow 2MgCO_3 + SiO_2$

Serpentine: $Mg_3Si_2O_5(OH)_4 + 3CO_2 \leftrightarrow 3MgCO_3 + 2SiO_2 + 2H_2O$

Wollastonite: $CaSiO_3 + CO_2 \leftrightarrow CaCO_3 + SiO_2$

World reserves >100 Mton (China, India, US, Finland), production 700 000 tons/y

Reserves estimated to exceed 9700 Gton just in the US

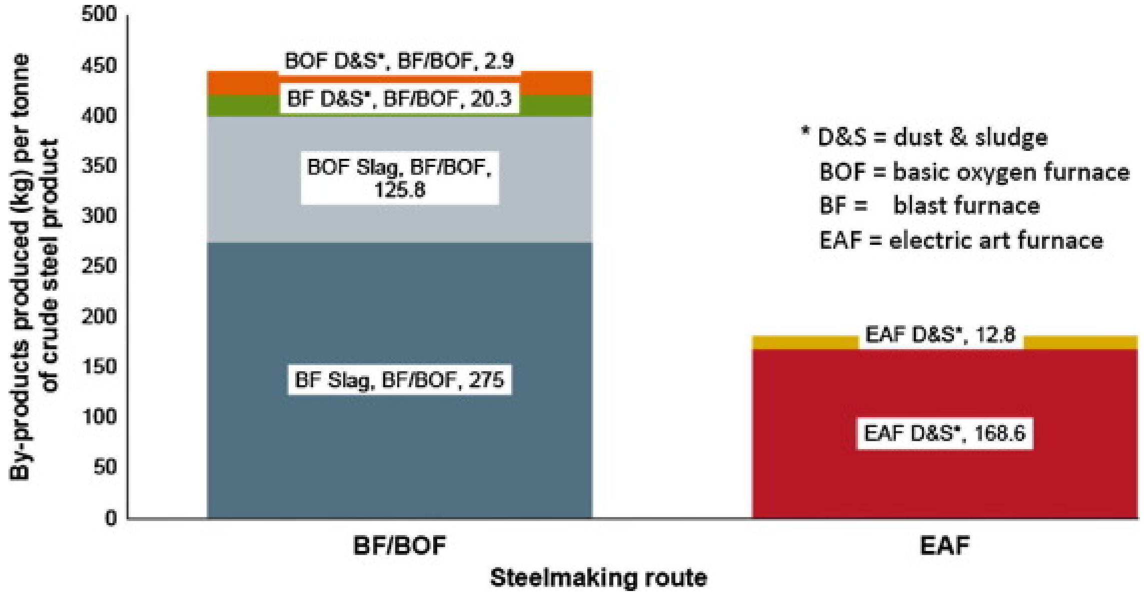
Feedstocks for carbon mineralization

- *Alkaline industrial residues*
  - **Steel industry**
    - ✓ Slag from converter units
    - ✓ Slag from steel refining treatments
    - ✓ Slag from stainless steel production
  - **Energy sector**
    - ✓ Pulverized fly ash
    - ✓ Lignite fly ash
    - ✓ Slag from thermal treatment processes
    - ✓ Air pollution control residues
    - ✓ Fly ash
  - **Cement industry**
    - ✓ Cement kiln dust
    - ✓ Waste cement

→ Total maximum sequestration potential ≈ 100s Mt CO_2/y

Feedstocks for carbon mineralization

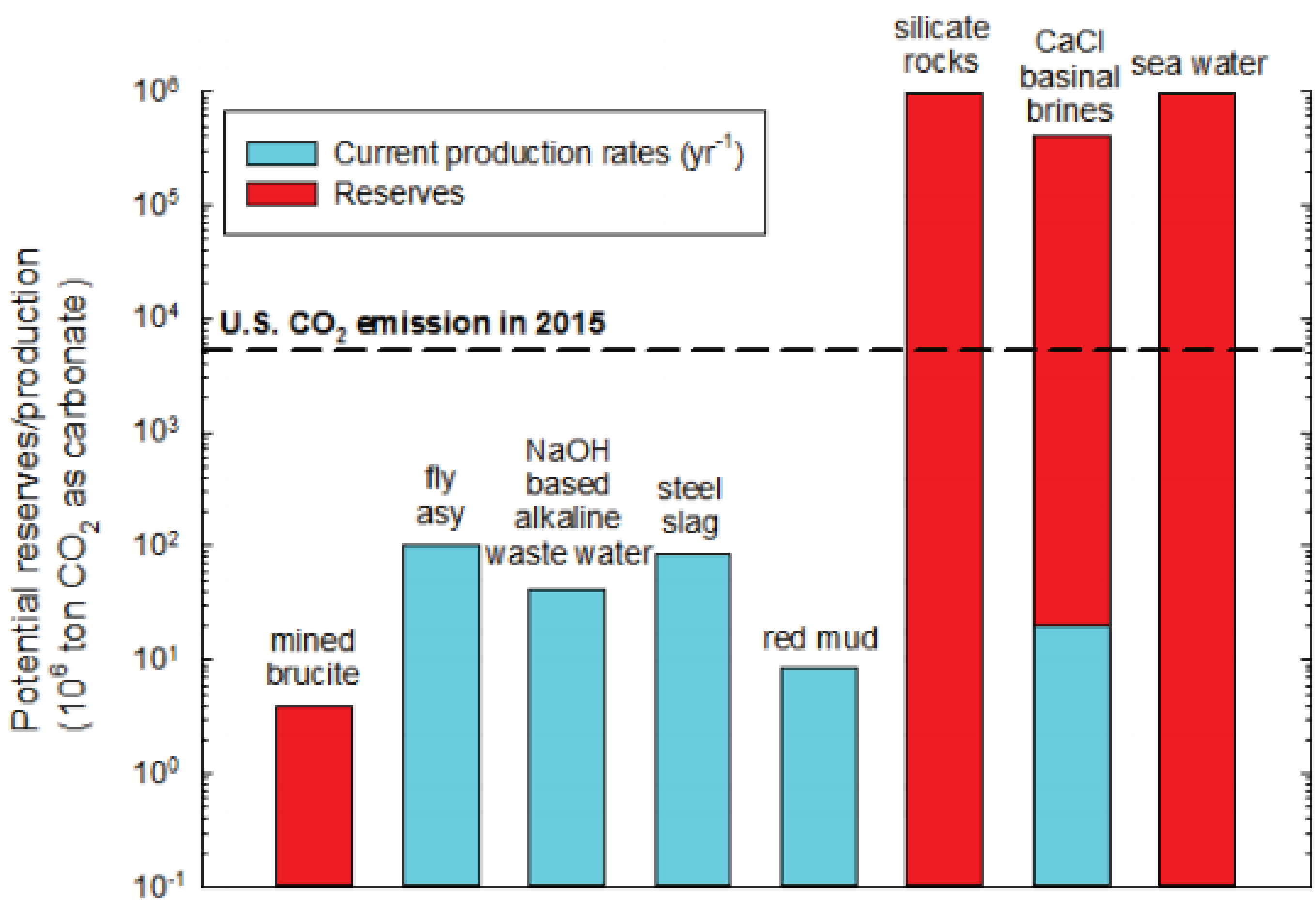
- *Steel slag production data (2014)*



On average the production of one ton of steel results in two tons of CO_2 emissions and 400 kg of blast and basic oxygen furnace slag, and 200 kg of electric arc furnace slag. Globally, more than 400 Mt of steel slag are produced annually.

Said et al, 2016

Feedstocks for carbon mineralization



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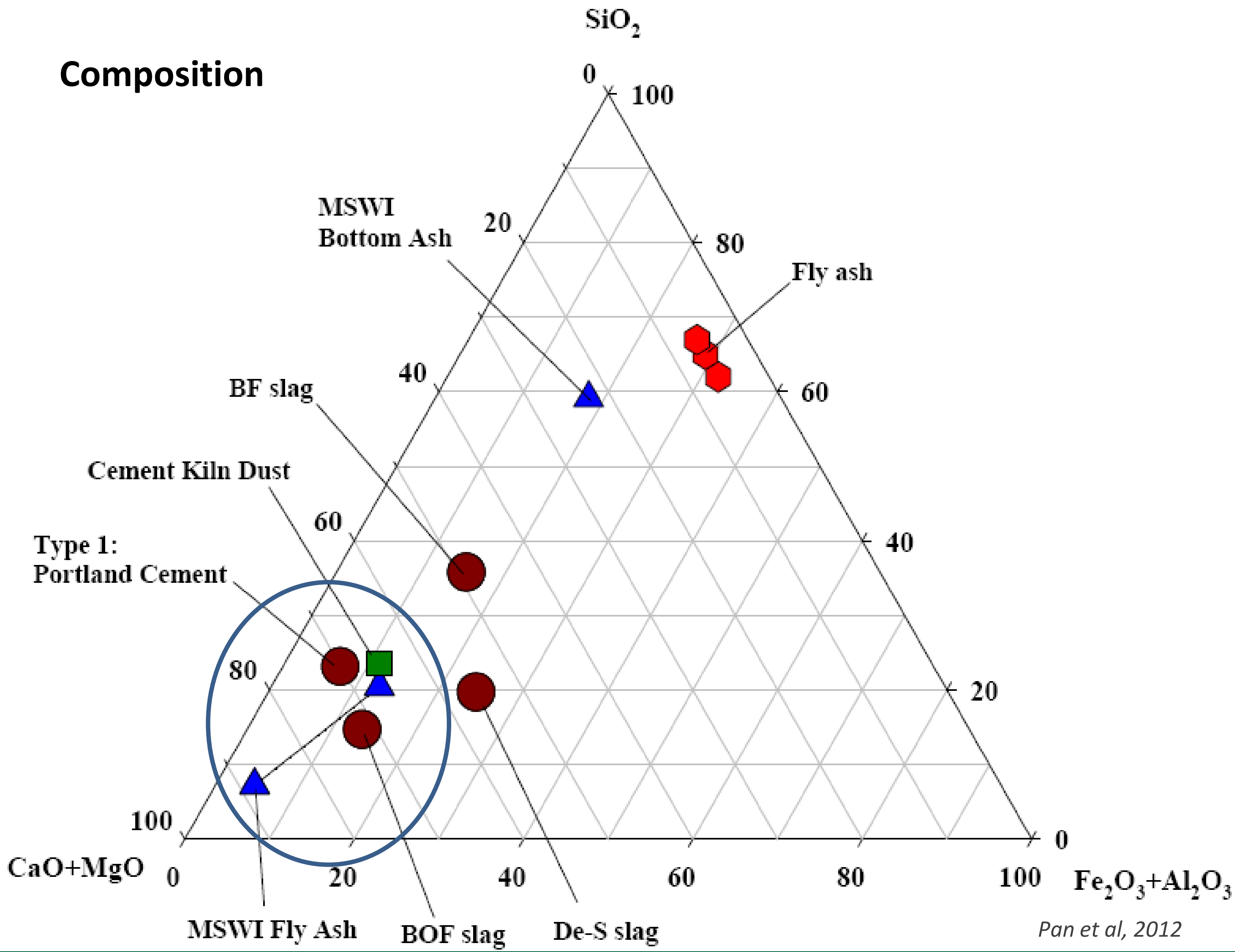
Feedstocks for carbon mineralization: residues versus minerals

- ✓ Often associated with CO_2 point source emissions and under used (or landfilled)
- ✓ No need for mining or quarrying
- ✓ Tend to be more unstable than geologically derived materials
- ✓ Require a lower degree of pre-treatment and less energy intensive conditions
- ✓ The product may present improved environmental and technical properties compared to the untreated residues

- ✗ Niche application with regard to CO_2 storage
- ✗ Composition and mineralogy may vary as a function of the industrial process

Feedstocks for carbon mineralization: residues

Composition



Pan et al, 2012

Feedstocks for carbon mineralization: residues

Mineralogy

	AOD1	EAF1	APC1	BOF1	BOF2	BOF3
Ca_2SiO_4	92.6%	75.5%	---	30.9%	---	12.1%
MgO	2.7%	4.2%	---	---	---	7.9%
$CaCO_3$	4.6%	3.6%	10.8%	5.9%	7.7%	4.0%
Fe_3O_4	0.1%	4.6%	---	19.6%	---	22.1%
CaF_2	0.0%	0.0%	---	---	---	---
SiO_2	---	2.9%	---	---	---	---
$Ca(OH)_2$	---	---	24.4%	26.6%	---	17.1%
$Mg(OH)_2$	---	---	---	17.0%	---	---
$CaSiO_3$	---	---	---	---	56.8%	---
FeO	---	---	---	---	35.5%	---
$NaCl$	---	---	13.8%	---	---	---
$CaOHCl$	---	---	51.0%	---	---	---
Ca_3SiO_5	---	---	---	---	---	32.1%
Cr_2O_3	0.1%	5.1%	---	---	---	---
MnO	---	---	---	---	---	4.6%
Al_2O_3	---	4.0%	---	---	---	---

Zingaretti et al, 2014

AOD1 and EAF1 Baciocchi et al., *Greenhouse Gases: Sci Technol*. 2012, 4: 312-19,
BOF1 and BOF3 Baciocchi et al., *Proc Crete 2012*
BOF 2 Huijgens et al., *Environ. Sci. Technol.*, 2005, 39: 9676-9682
APC1 Baciocchi et al., *Waste Manage* 2009, 29: 2994-3003

$$Ca_2SiO_4 + 2CO_2 \rightarrow 2CaCO_3 + SiO_2$$
$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$
$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$$
$$2CaOHCl + CO_2 \rightarrow CaCO_3 + CaCl_2 + H_2O$$
$$Ca_3SiO_5 + 3CO_2 \rightarrow 3CaCO_3 + SiO_2$$
$$MgO + 2CO_2 + CaO \rightarrow MgCa(CO_3)_2$$
$$Mg(OH)_2 + 2CO_2 + CaO \rightarrow MgCa(CO_3)_2 + H_2O$$

Carbon mineralization products

Depending on the treatment route applied a wide range of products and by-products can be obtained.

Process adaptation or post-processing can be employed to further expand the range of products to include higher-value ones.

Aggregates (Carbon8)

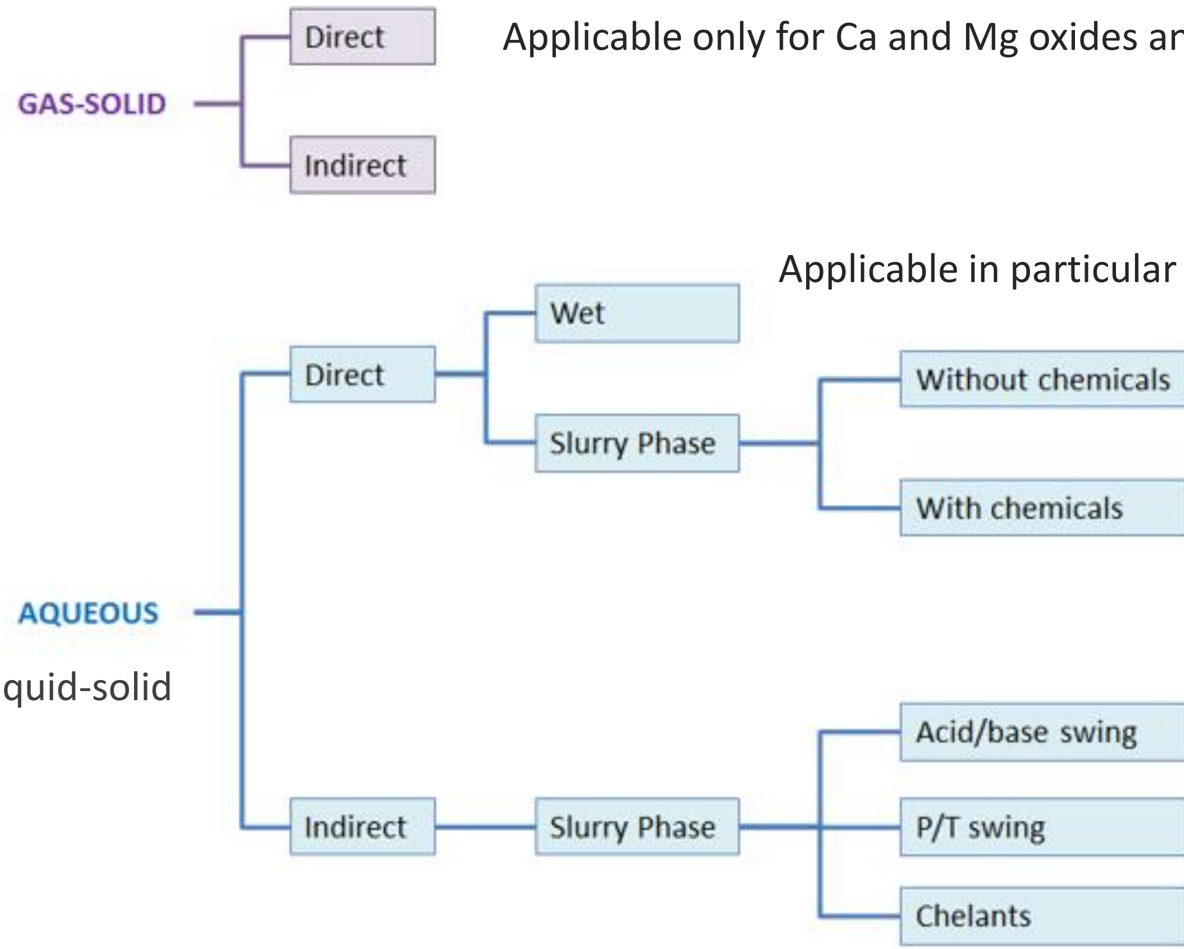
Blocks (Carbstone-innovation)

Precipitated calcium carbonate for paper coating applications as well as mineral fillers for plastics

Carbon mineralization process routes

Applicable only for Ca and Mg oxides and hydroxides

Applicable in particular for Ca-based residues



gas-liquid-solid

Baciocchi et al, 2014

Aqueous route: dissolution and precipitation

$$CO_{2(g)} + H_2O_{(l)} \rightarrow H_2CO_{3(aq)} \rightarrow H^+_{(aq)} + HCO^-_{3(aq)}$$

$$Mg_2SiO_{4(s)} + 4H^+_{(aq)} \rightarrow 2Mg^{2+}_{(aq)} + SiO_{2(s)} + 2H_2O_{(l)}$$

Dissolution
high T and low pH

$$Mg^{2+}_{(aq)} + HCO^-_{3(aq)} \rightarrow MgCO_{3(s)} + H^+_{(aq)}$$

Precipitation
high pH

Single-step: dissolution + precipitation (in a single reactor)

Multi-step: dissolution and precipitation are separately optimized

Two or more steps are needed when dissolution conditions are too far from those required for precipitation or when a high purity product is required

Additives for the direct step: Bicarbonate/Salt mixture ($NaHCO_3$/NaCl) proposed to accelerate the reaction

Example of indirect process routes

Maroto-Valer et al., (Penn State Research Fundation,US) patents 2004 (WO),2005 (US)

- Aqueous mineral carbonation / Two step process
- Materials: silicate-based Ca/Mg minerals or materials (olivine, serpentine, waste cement)
- Particle size: 70-150 µm
- Step 1: chemical activation with an acid: T=15 - 75°C; 3-12 hours time

$$Mg_3Si_2O_5(OH)_4 + 3\ H_2SO_4 \dashrightarrow 3\ MgSO_4 + 5\ H_2O + 2\ SiO_2$$

- Step 2a: Use of a base (KOH, NaOH, $NaHCO_3$, Acetates, Formates (pH=7-14)

$$MgSO_4 + 2\ NaOH \dashrightarrow Mg(OH)_2 + Na_2SO_4$$

- Step2b: addition of $Ca(NO_3)_2$

$$MgSO_4 + Ca(NO_3)_2 + 2\ H_2O \dashrightarrow CaSO_4 \cdot 2H_2O + Mg(NO_3)_2$$

$$Mg(NO_3)_2 + Ca(OH)_2 \dashrightarrow Mg(OH)_2 + Ca(NO_3)_2$$

- Step 3: Mg carbonate precipitation and acid recovery (reaction with CO_2)

$$Mg(OH)_2 + CO_2 \dashrightarrow MgCO_3 + H_2O \qquad MgSO_4 + H_2CO_3 \dashrightarrow MgCO_3 + H_2SO_4$$

Maroto-Valer et al., (Penn State Research Fundation, US) patents 2004 (WO),2005 (US)

- Step 1: dissolution of the mineral (serpentine)

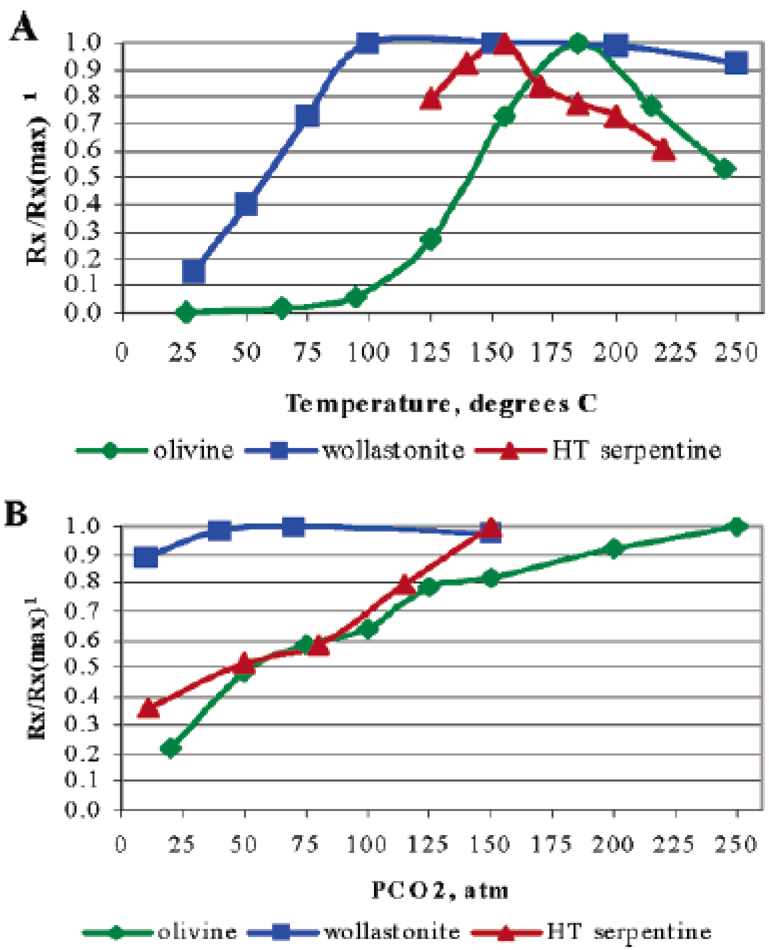
Treatment	% Mg^{2+} in solution	Activation Conditions
Sulfuric Acid	71	25°C, 12 hours
Hydrochloric Acid	21	25°C, 12 hours
Phosphoric Acid	25	25°C, 12 hours
Acetic Acid	48*	60°C, 4 hours*

* Maximum extraction yield reported in the literature using acetic acid (Kakizawa et al., 2001).

- Step 2: conversion of $Mg(OH)_2$ /$MgSO_4$ to $MgCO_3$

Sample	Conversion	Carbonation Conditions
Parent, untreated	8 %	155°C, 1850 psig, 1 hour
Steam treated	70%	155°C, 1850 psig, 1 hour
$Mg(OH)_2$	>55%	20°C, 650 psig, 3 hours
$MgSO_4$	54%	20°C, 650 psig, 6 hours
Mg Acetate	30%	20°C, 650 psig, 3 hours

Single step aqueous carbon mineralization



Optimum carbonation conditions

mineral	carbonation conditions		
	T, °C	P_{CO_2}, atm	carrier solution
olivine	185	150	0.64 M $NaHCO_3$, 1 M NaCl
wollastonite	100	40	distilled water
HT serpentine	155	115	0.64 M $NaHCO_3$, 1 M NaCl

Samples ground to < 75µm

HT: Heat treatment at 630 °C for 2 hours

R_x= extent of reaction in 1h

R_x(max) = maximum extent of reaction in 1h

olivine: 49.5%

wollastonite: 81.8%

HT serpentine: 73.5%

Gerdemann et al. (2007)

Example of an indirect process route for residues

Teir et al., (Abo Academy Finland, patent 2013 (WO)

The calcium extraction stage

$$2CaO_{(s)} \cdot SiO_{2(s)} + 2NH_4Cl_{(aq)} + H_2O_{(l)} \leftrightarrows CaCl_{2(aq)} + CaO_{(s)} \cdot SiO_{2(s)} + 2NH_4OH_{(aq)}, \quad \Delta H\,(20\,^{\circ}C) = -49,382\ kJ, \qquad (R1)$$

$$CaO_{(s)} + 2NH_4Cl_{(aq)} + H_2O_{(l)} \leftrightarrows CaCl_{2(aq)} + 2NH_4OH_{(aq)} \quad \Delta H\,(20\,^{\circ}C) = -87,964\ kJ, \qquad (R2)$$

and the carbonation reactions

$$CO_{2(g)} \rightleftarrows CO_{2(aq)} \quad \Delta H\,(20\,^{\circ}C) = -21,101\ kJ, \qquad (R3)$$

$$2NH_4OH_{(aq)} + CO_{2(g)} \leftrightarrows (NH_4)_2CO_{3(aq)} + H_2O_{(l)} \quad \Delta H\,(20\,^{\circ}C) = -109,231\ kJ,$$

$$(NH_4)_2CO_{3(aq)} + CaCl_{2(aq)} \leftrightarrows CaCO_{3(s)} + 2NH_4Cl_{(aq)} \quad \Delta H\,(20\,^{\circ}C) = 19,000\ kJ.$$

Slag 2 PCC

Ammonium salts (NH_4Cl, H_4NO_3 or $CH_3COONH4$)
Dissolution at 20°C

Pilot plant in operation

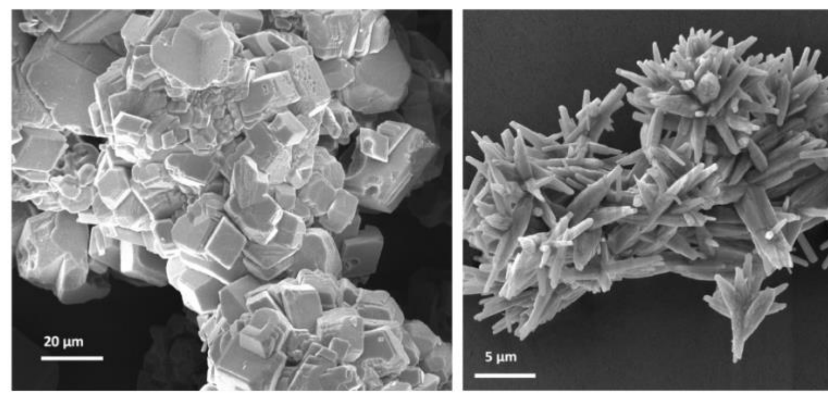


Fig. 13. SEM micrographs of PCC produced from the Slag2PCC pilot plant: (a) Test 1 at 20 °C, rhombohedral calcite and (b) Test 2 at 45 °C, aragonite.

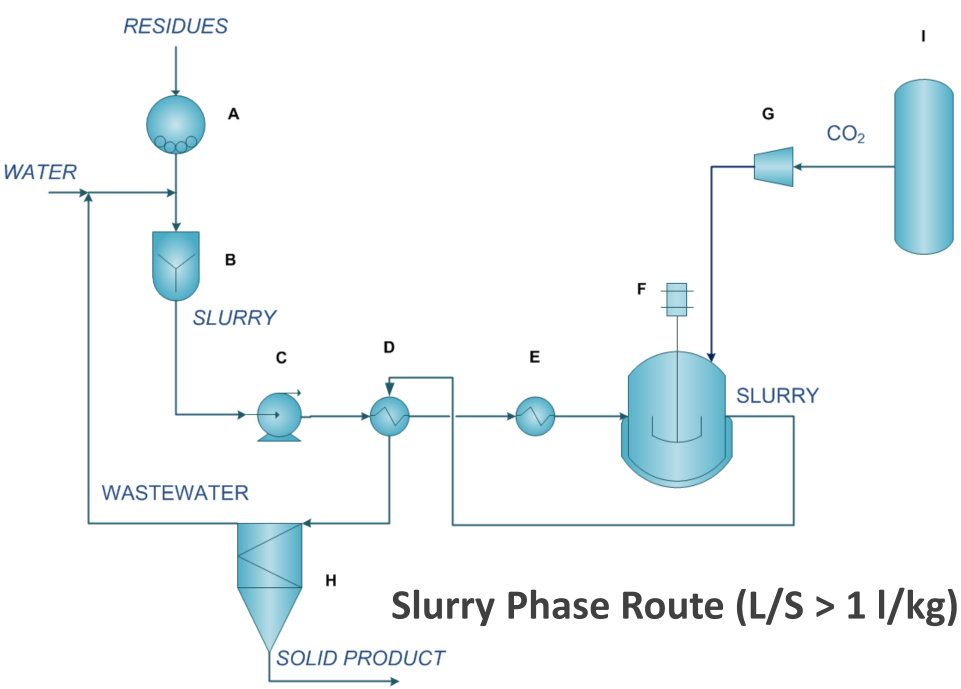
Said et al 2016

Carbonation T < 60 °C to avoid ammonia emissions

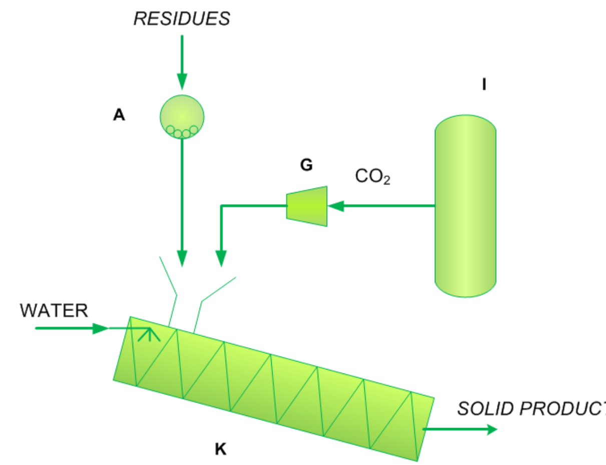
Direct aqueous carbonation of residues

SLURRY PHASE ROUTE (L/S>2 l/kg): T=50-150 °C and p_{CO2}=1-20 bar

WET ROUTE (L/S<1 l/kg): T=20-50 °C and p_{CO2}=1-10 bar



Slurry Phase Route (L/S > 1 l/kg)

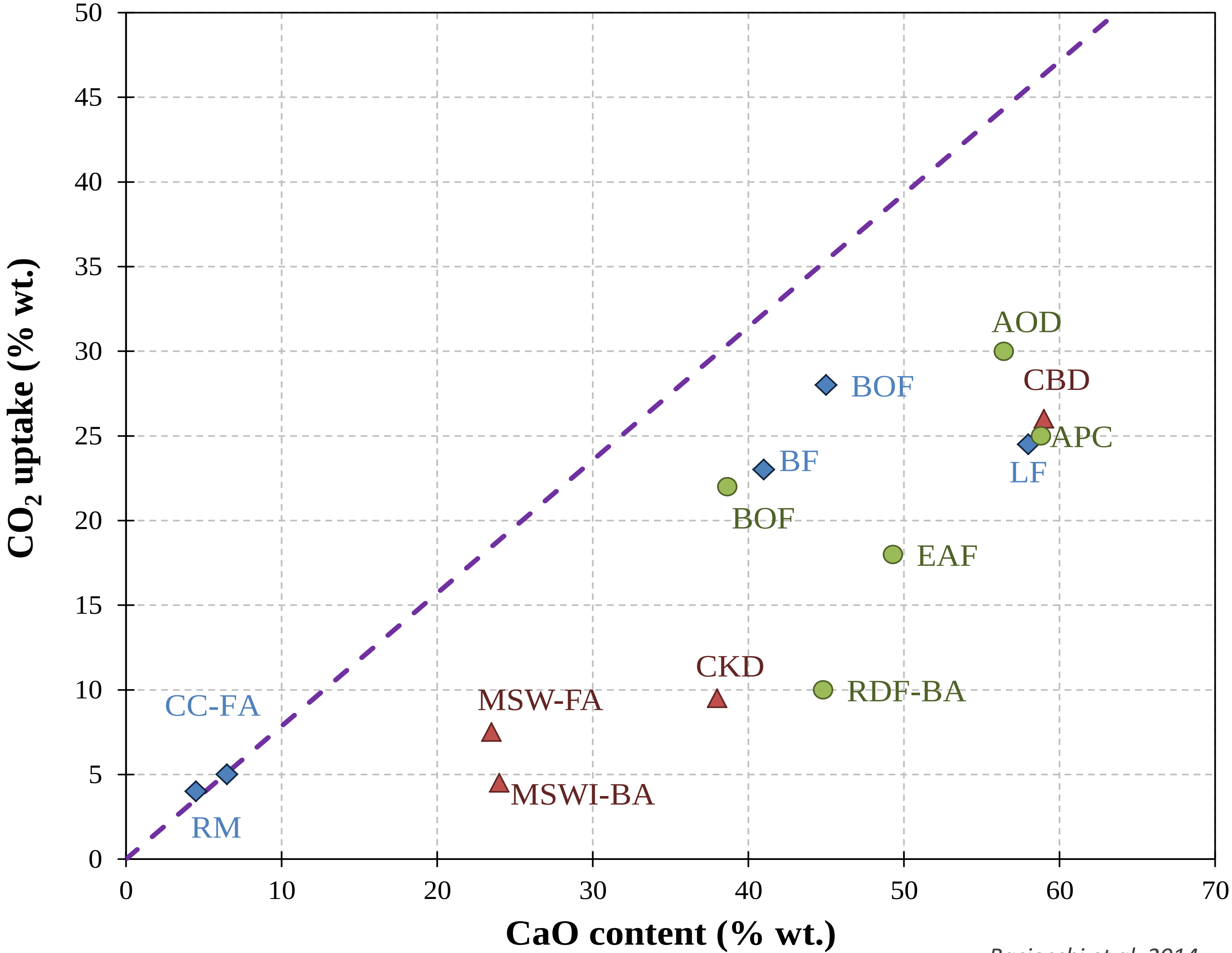


Wet route (L/S < 1 l/kg)

Zingaretti et al, 2014

A	Mill	**F**	Carbonation Reactor
B	Mixer	**G**	Compressor
C	Slurry Pump	**H**	Clarifier
D	Heat Exchanger	**I**	CO_2 Absorber
E	Heater	**K**	Rotary Drum Reactor

CO_2 uptake as a function of waste composition

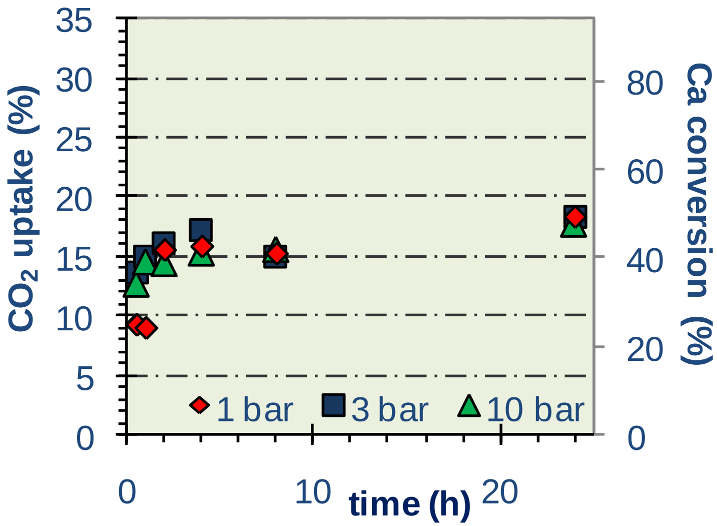


Bariocchi et al, 2014

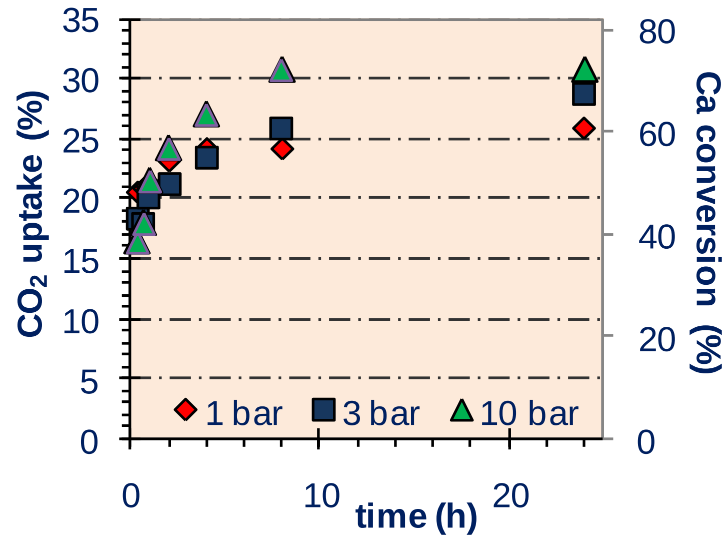
CO_2 uptake as a function of waste mineralogy

50 °C
L/S=0.4 l/kg
100% CO_2

EAF slag



AOD (ladle) slag

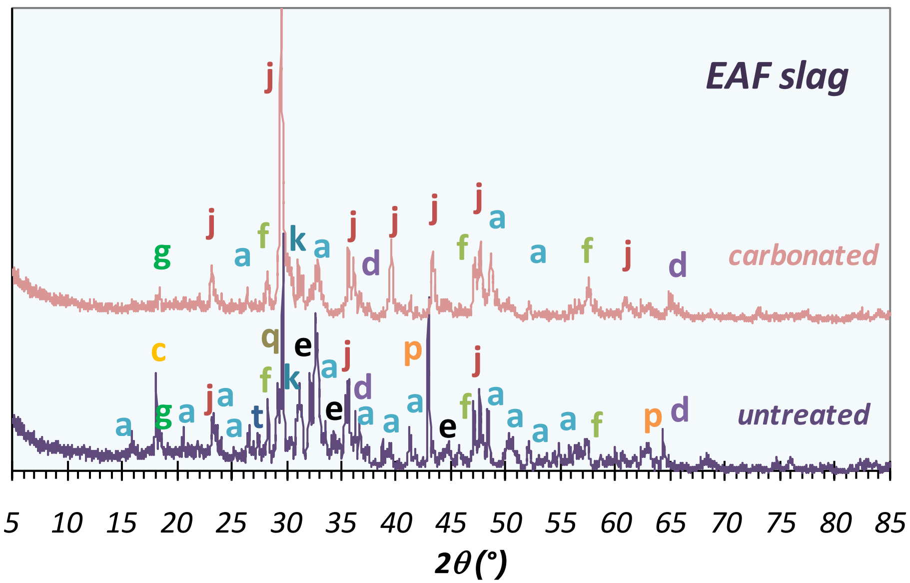


Baciocchi et al, 2012

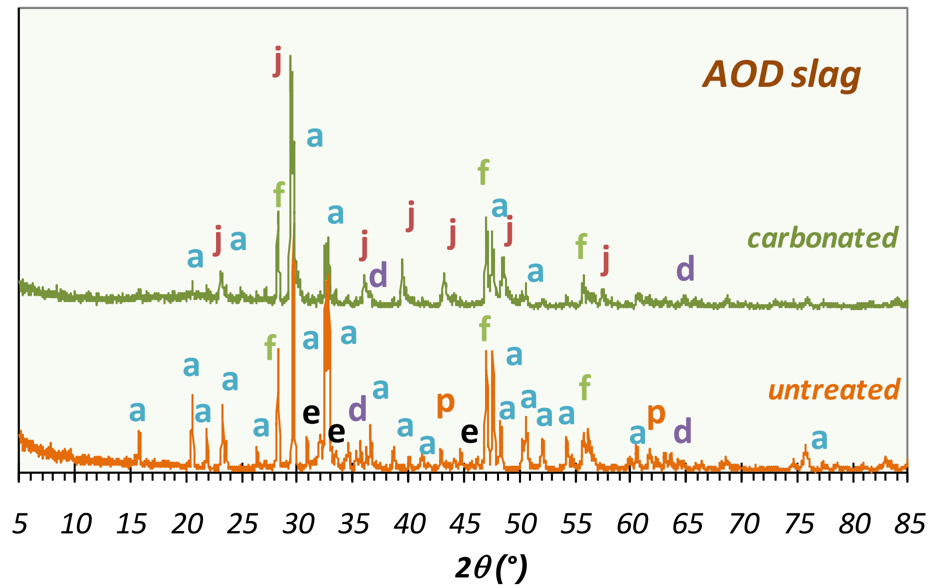
For residues with high contents of $Ca(OH)_2$ (e.g. APC residues), Ca conversions of over 60% were found for t<30 min at ambient T and pCO_2 = 1 bar for L/S ratios of 0.2 l/kg

CO_2 uptake as a function of waste mineralogy

Carbonation conditions: 4 h and 10 bar



Carbonation conditions: 2 h and 1 bar

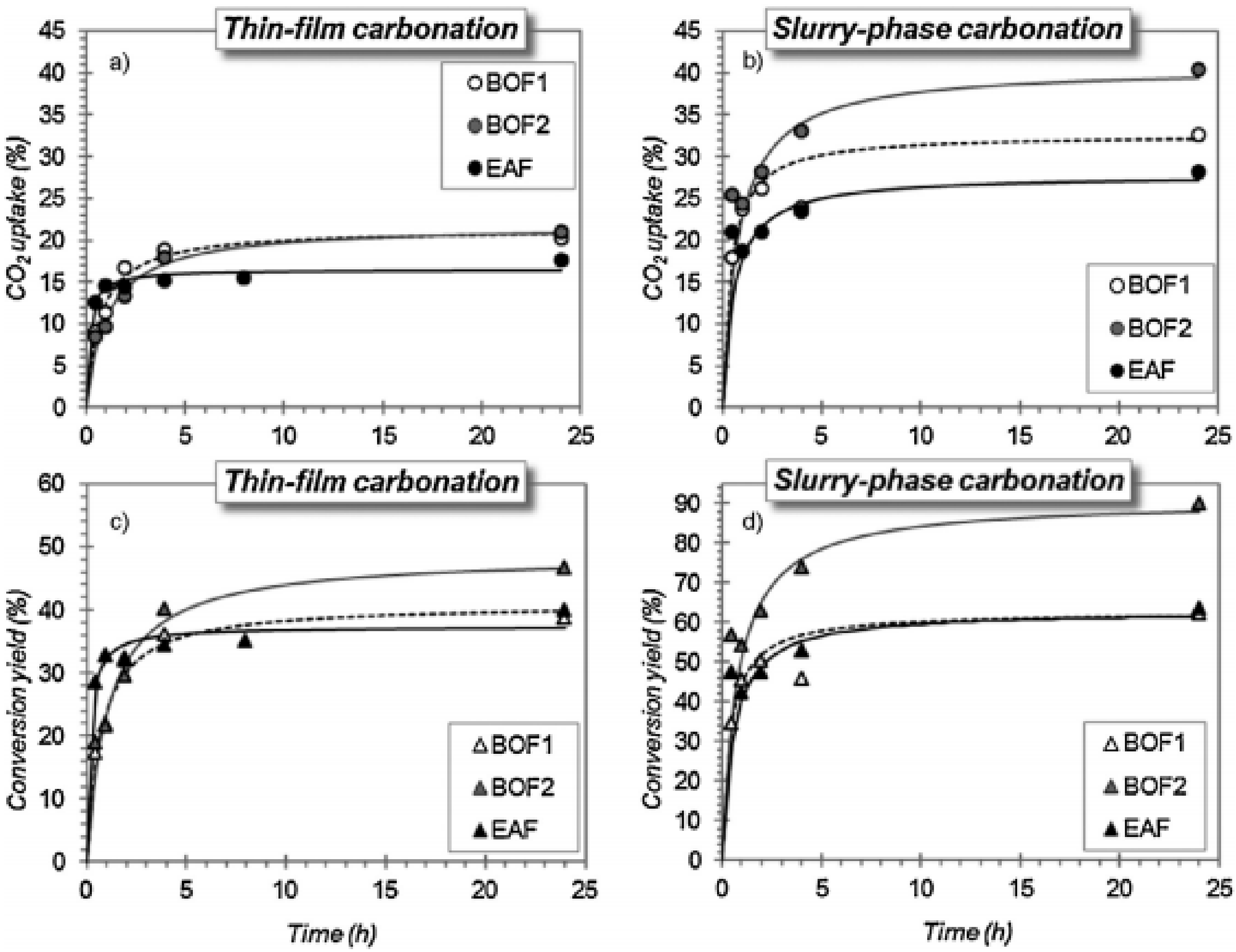


Baciocchi et al, 2012

- *a) dicalcium silicate (Ca_2SiO_4)*
- *c) Ca-Al oxide ($Ca_{12}Al_{14}O_{33}$)*
- *d) magnetite (Fe_3O_4)*
- *e) chromium oxide (CrO)*
- *f) calcium fluoride (CaF_2)*
- *g) Cr-Mg oxide ($MgCr_2O_4$)*
- *j) calcite ($CaCO_3$)*
- *k) gehlenite ($Ca_2Al_2SiO_7$) or akermanite ($Ca_2MgSi_2O_7$)*
- *p) periclase (MgO)*
- *q) cuspidine ($Ca_4Si_2O_7(F,OH)$)*
- *t) quartz (SiO_2)*

CO_2 uptake as a function of process route and operating conditions

50 °C
10 bar
L/S=0.3 l/kg
100% CO_2



100 °C
10 bar
L/S=5 l/kg
100% CO_2

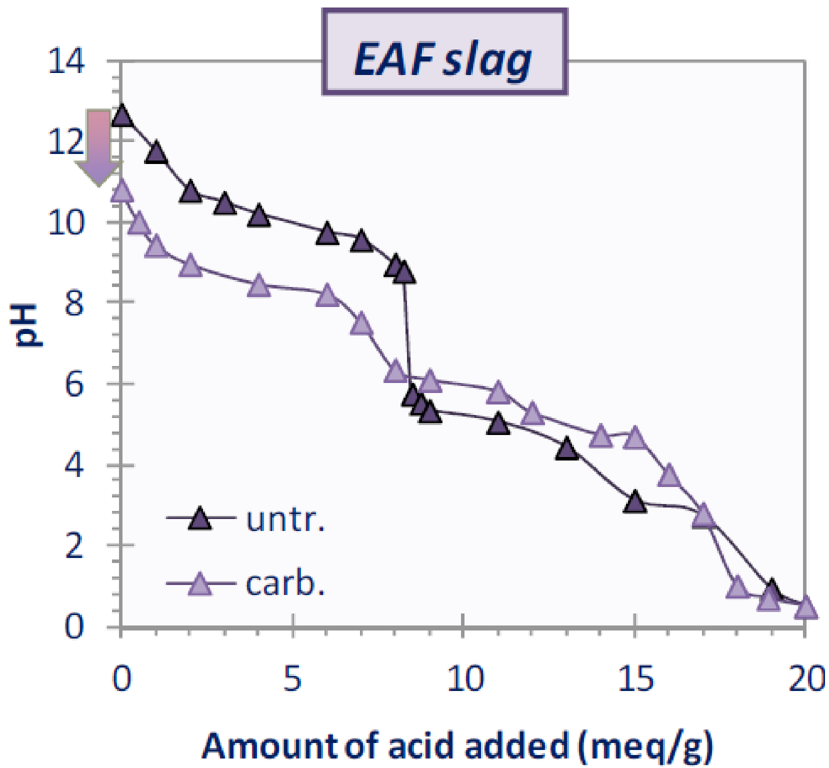
For the slurry route dolomite was found in the product so Mg was considered in the conversion yield

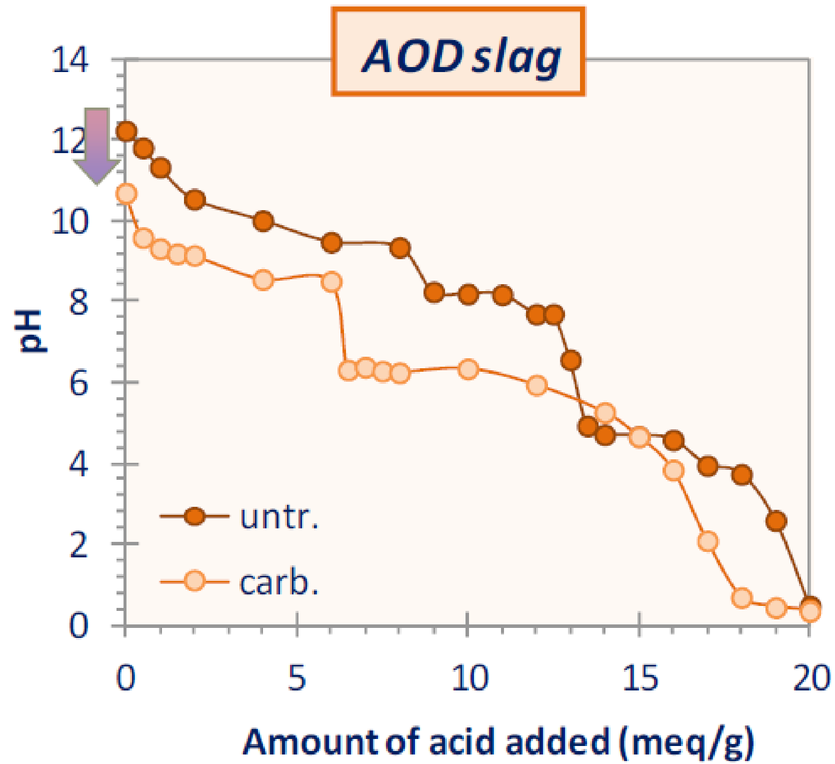
Samples milled to below 150 μm

Baciocchi et al, 2015

Effects on leaching behavior for wet route carbonation

- Acid neutralization capacity

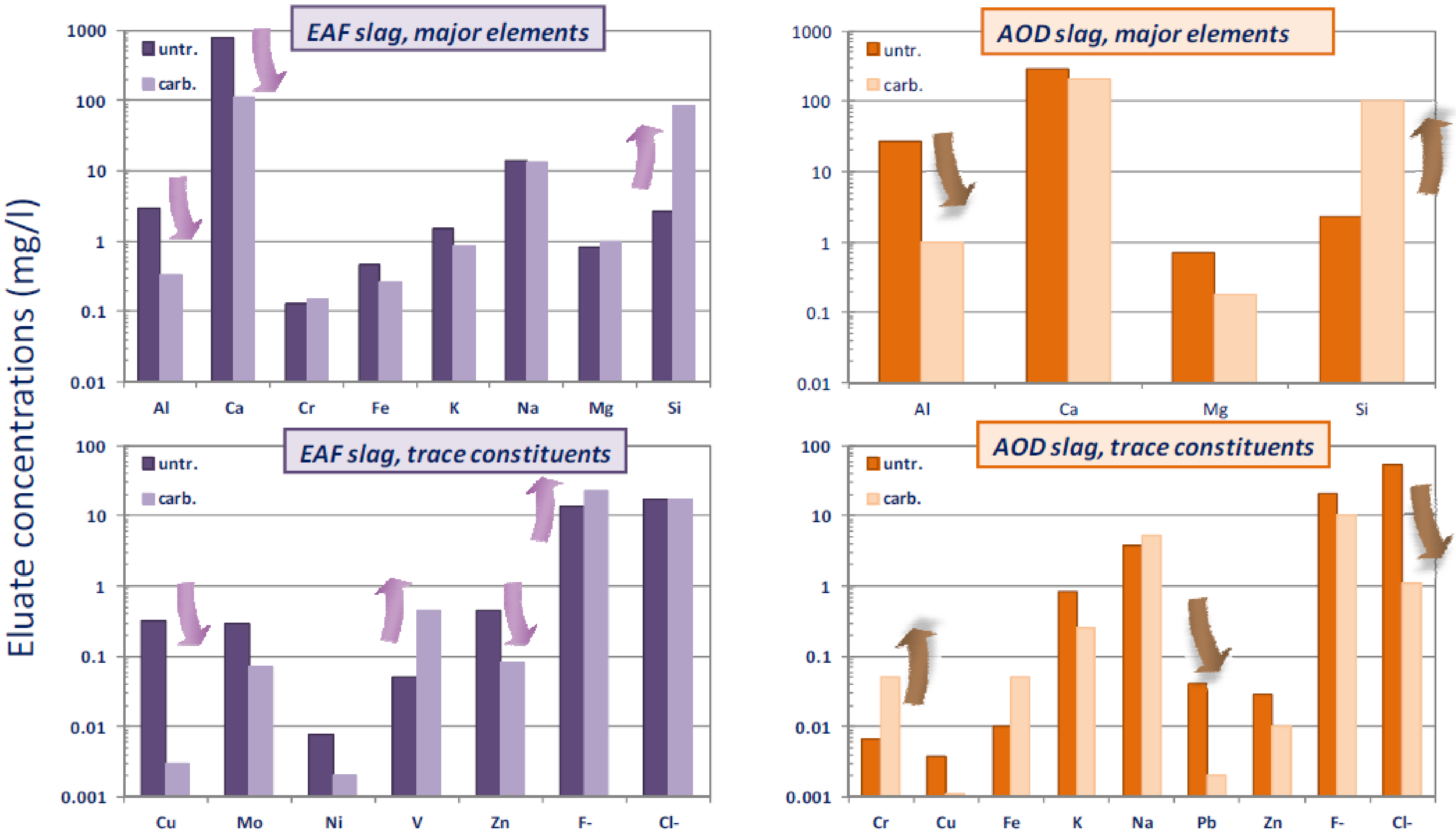




Carbonation conditions: 50 °C, L/S=0.4 l/kg, 100% CO_2

Baciocchi et al, 2012

Effects on leaching behavior for wet route carbonation



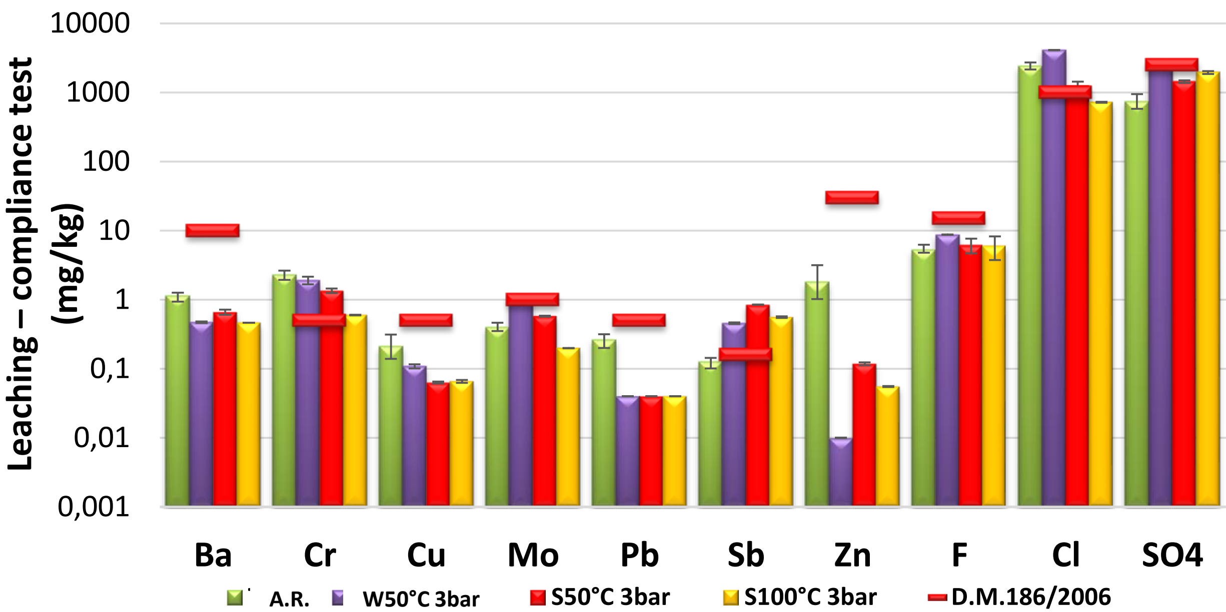
pH: 12.6 → 10.8

Baciocchi et al, 2012

pH: 12.5 → 10.5

Effects on leaching behavior: wet vs. slurry route carbonation

Tests performed on a sample of BA from dry waste incineration



	pH	$CO_{2uptake}$(%)
A. R.	12.5	-
W50°C 3bar	9.8	11.31
S50°C 3bar	10.4	9.95
S100°C 3bar	10.7	9.38

Slurry carbonation at 100 °C

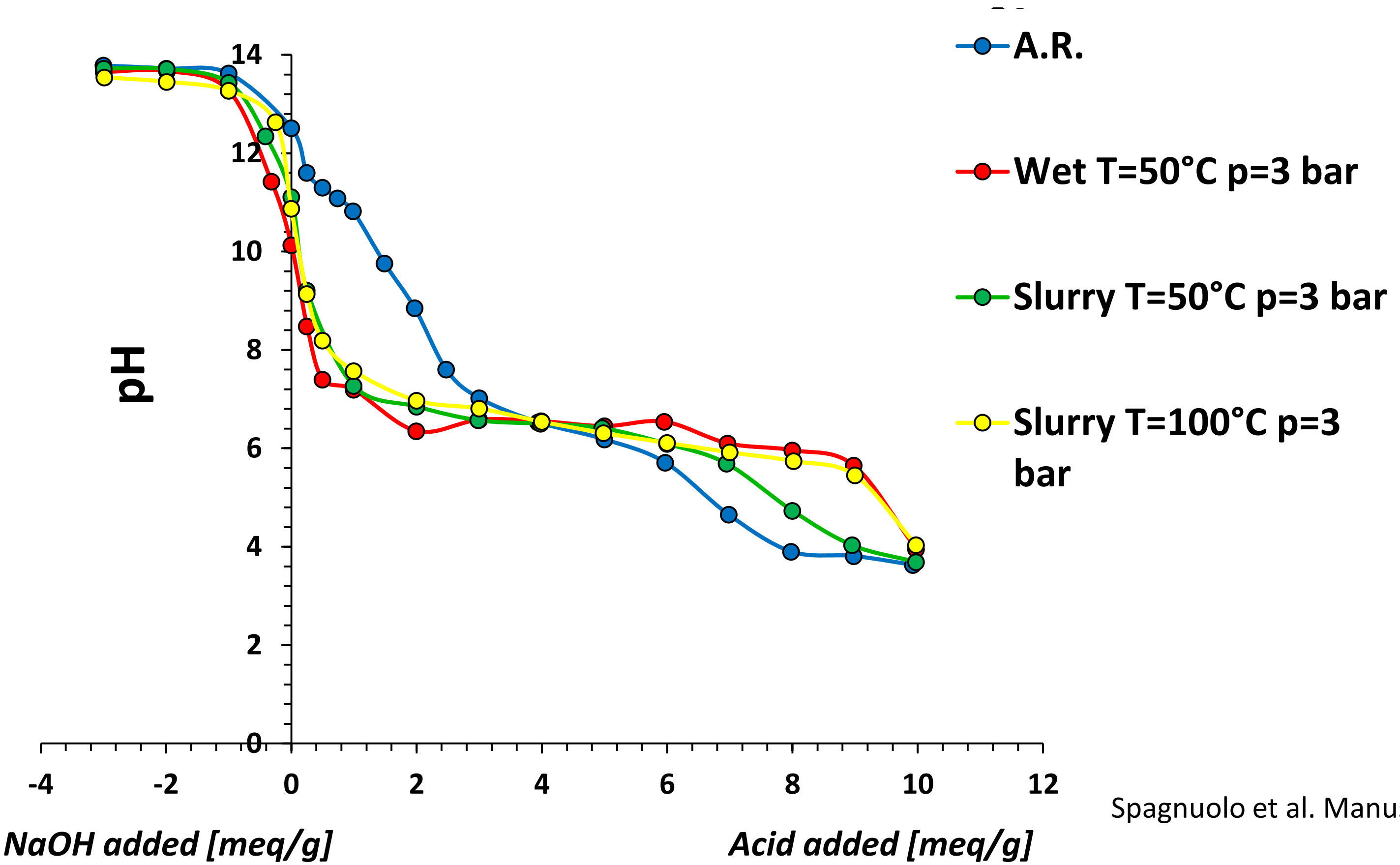
√ pH, Cr and Cl

X Sb

Spagnuolo et al. Manuscript in preparation

Effects on leaching behavior: wet vs. slurry route carbonation

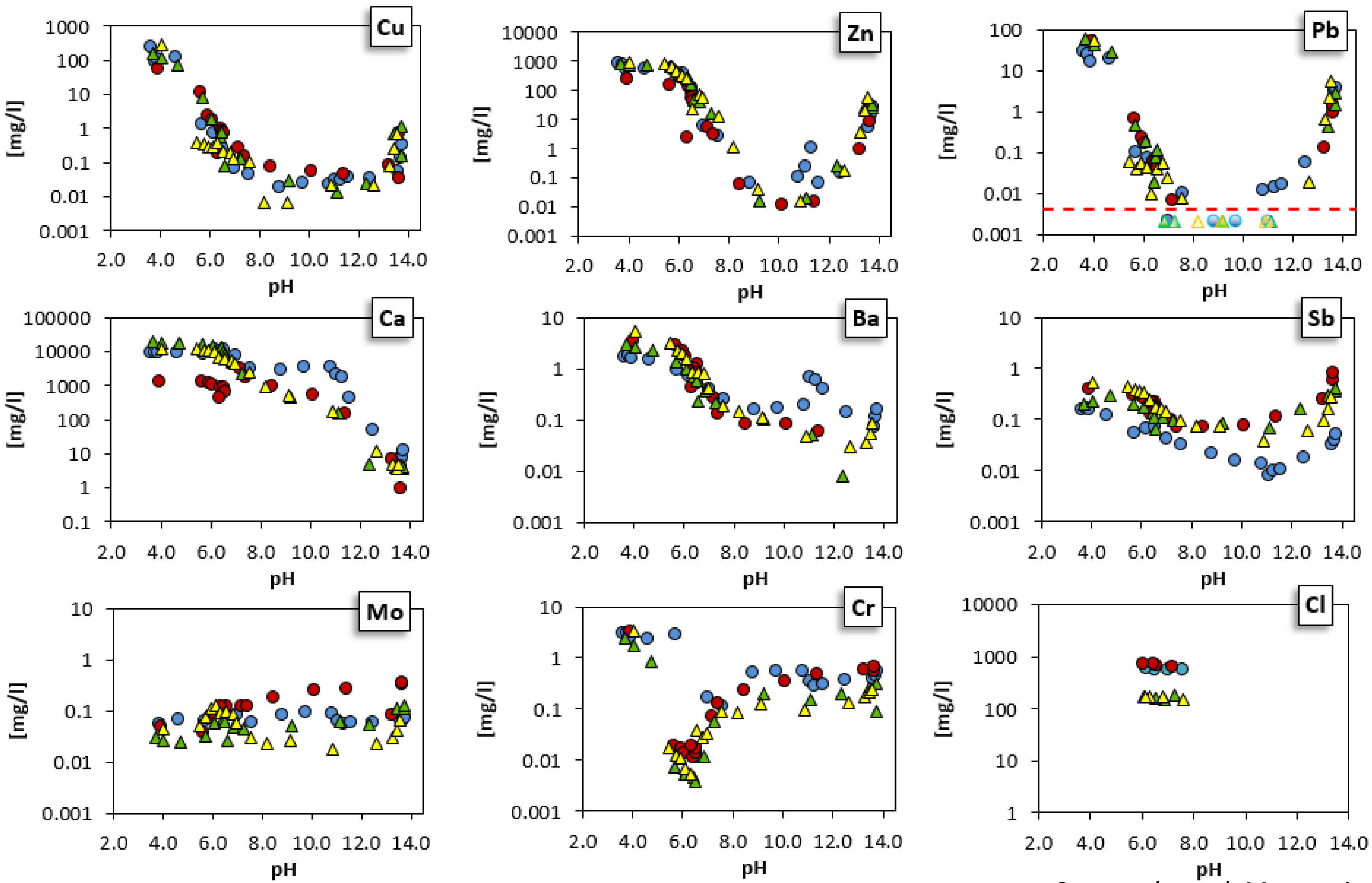
Tests performed on a sample of BA from dry waste incineration: ANC behaviour



Spagnuolo et al. Manuscript in preparation

Effects on leaching behavior: wet vs. slurry route carbonation

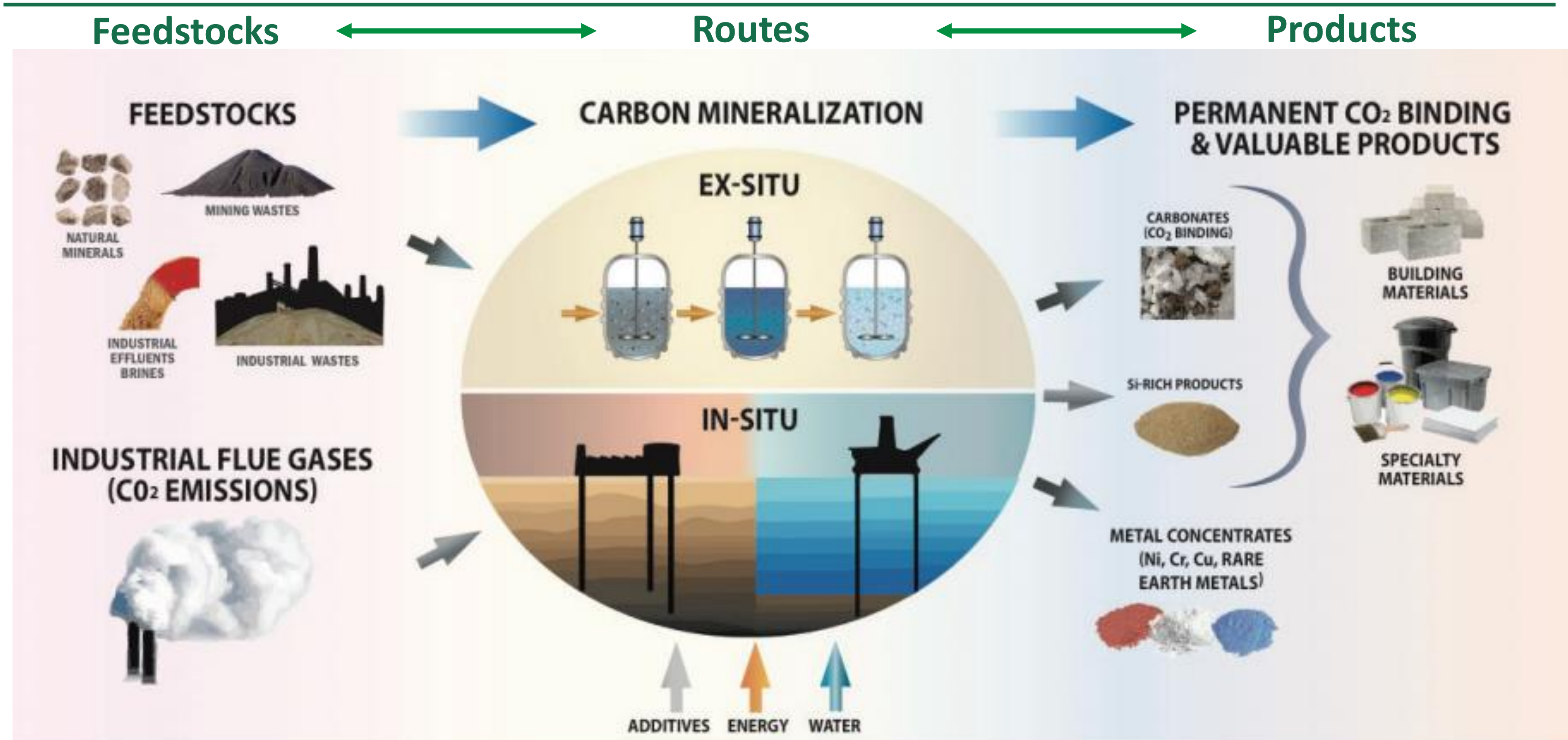
Results: *Release as a function of pH*



Spagnuolo et al. Manuscript in preparation

● A.R. ● Wet T=50°C, p=3 bar ▲ Slurry T=50°C, p=3 bar △ Slurry T=100°C, p=3 bar - - - LOQ

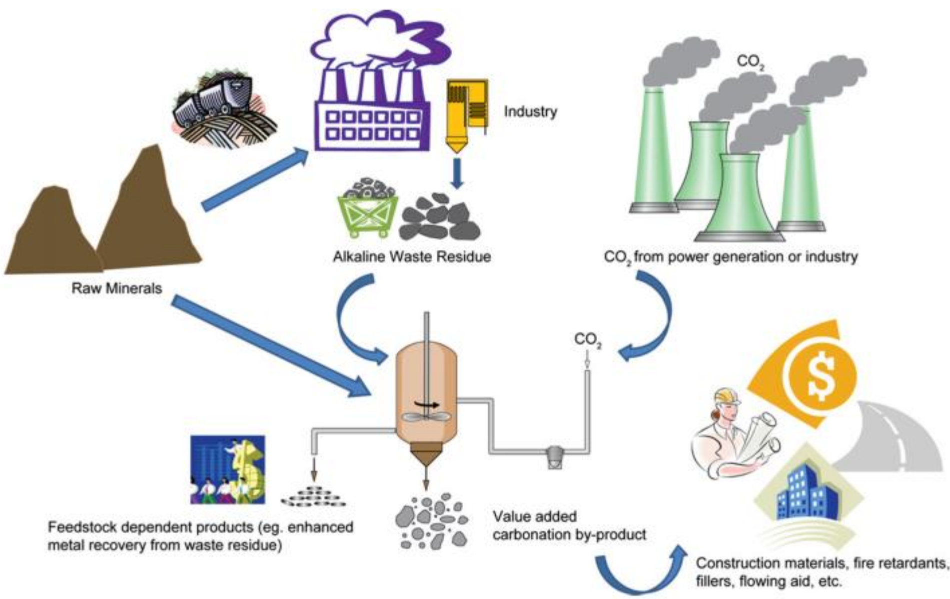
Applications of carbon mineralization



MI Expert workshop on CCUS report, 2017

- **Ex situ engineered processes (minerals & industrial residues)**
- In-situ passive weathering (mine tailings)
- Ex situ treatment or curing step (cements/concrete)

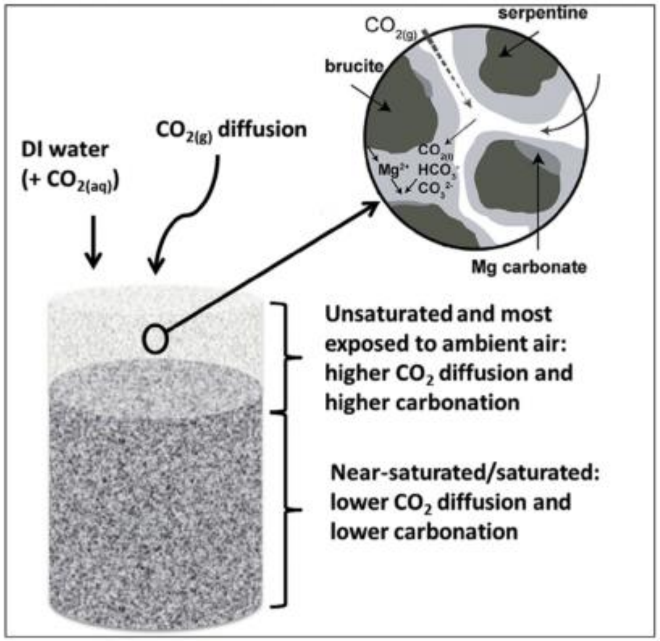
Ex situ carbonation of minerals (Mg-bearing silicate rocks) and alkaline waste residues



Bobicki et al. 2011

- CCS and/or CCU
- Many types of process routes tested
- Multi-step processes for minerals (serpentine)
- Energy-intensive pre-treatment usually required
- Need for recycling additives employed for enhancing dissolution kinetics
- Need to produce a product with specific technical properties for utilisation (e.g. purity, particle size, morphology)
- Issues on effects of treatment on environmental behaviour of waste materials
- Direct use of diluted CO_2 sources to avoid capture would be very important

Passive mineralization of atmospheric CO_2 in mine waste/tailings

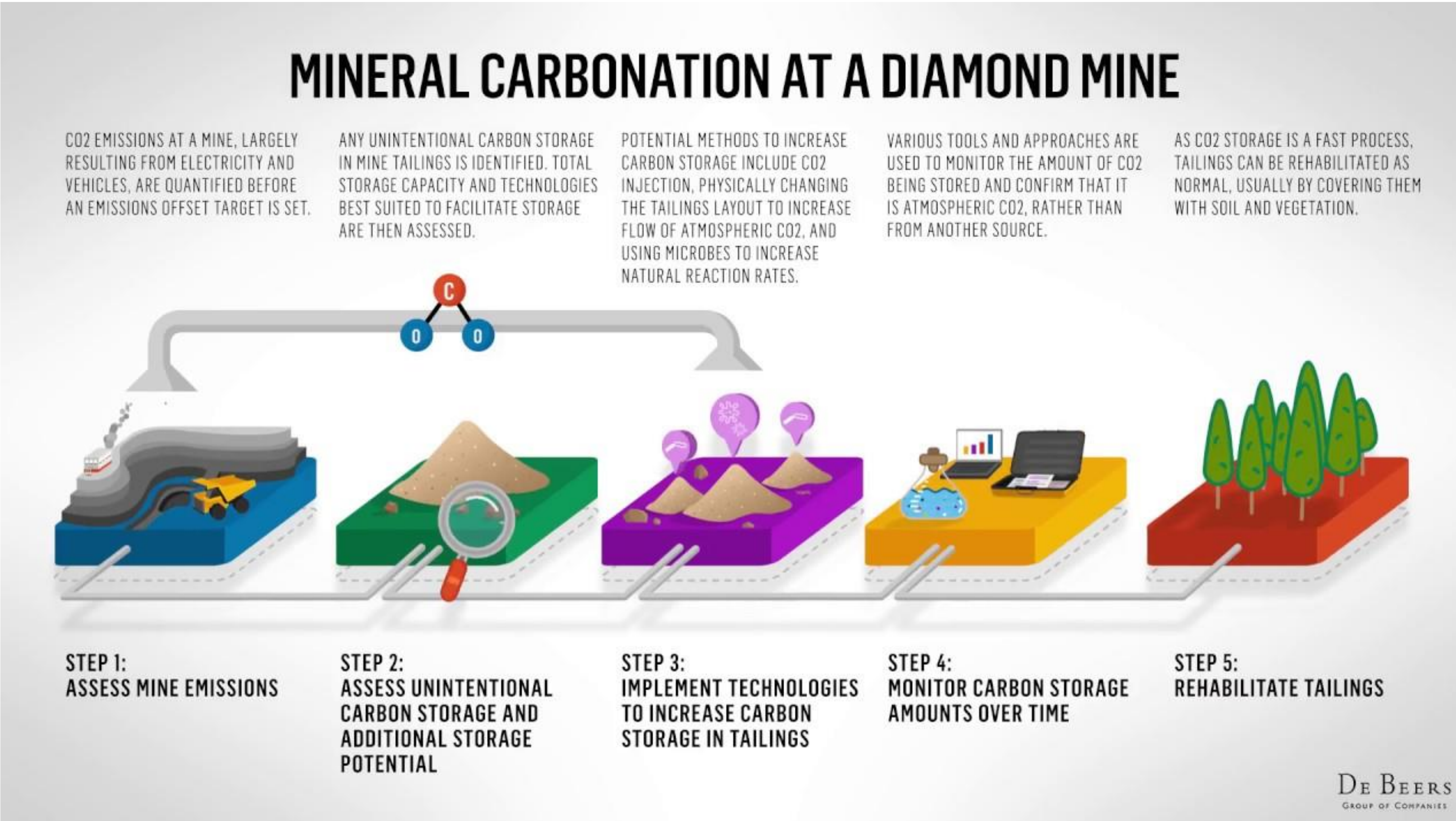


Kandji et al 2017

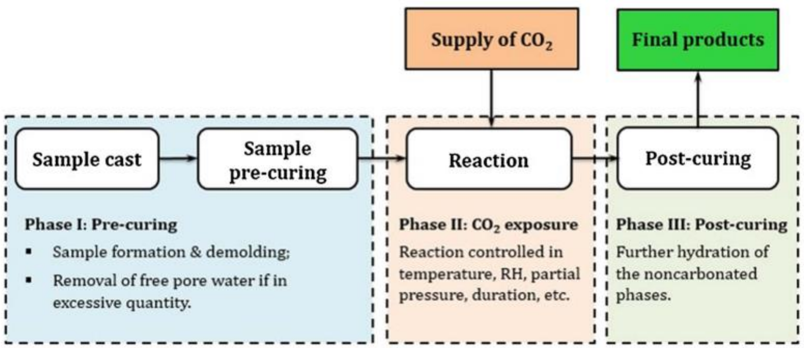
- Direct air capture or permanent storage (or use) of carbon point sources
- Stabilization of mining waste and improvement of environmental properties (e.g. chrysotile)
- Monitoring uptakes with different methods (e.g. carbon footprinting)
- Need to accelerate CO_2 gas dissolution and hydration processes at ambient temperature to increase uptakes
- Need to engineer the process
- Need to monitor and predict the leaching behaviour of the waste (geochemical modelling)

Serpentine Tailings

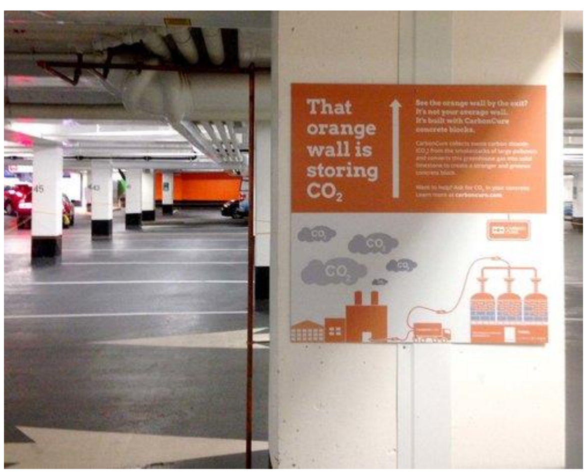
Passive mineralization of atmospheric CO_2 in mine waste/tailings



CO_2 utilization for concrete production



Typical lab-scale procedure (Zhang et al. 2017)



CarbonCure

- Natural weathering is well known to cause detrimental long term effects on concrete (cracking and strength loss) but early stage concrete curing under a CO_2 atmosphere can improve product properties and store CO_2
- Cement phases, $Ca(OH)_2$ and C-S-H, react with CO_2 forming micro-sized calcite crystals that can fill pores, even repair micro-cracks and improve compressive strength
- Other applications investigated: use of carbonated aggregates for concrete production, enhance hydraulic properties of silicate phases found in residues, facilitate 3D printing of cement based materials
- Long term stability and durability of products needs to be investigated as well as the evolution of product-layers and diffusion mechanisms in the system

Slag Valorisation Symposium

Science, Innovation & Entrepreneurship in Pursuit of a Sustainable World

01-05 April 2019

Mechelen, Belgium

Carbonation Workshop

Other material for roundtable discussion: energy requirements and open issues identified at MI workshop

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Energy requirements

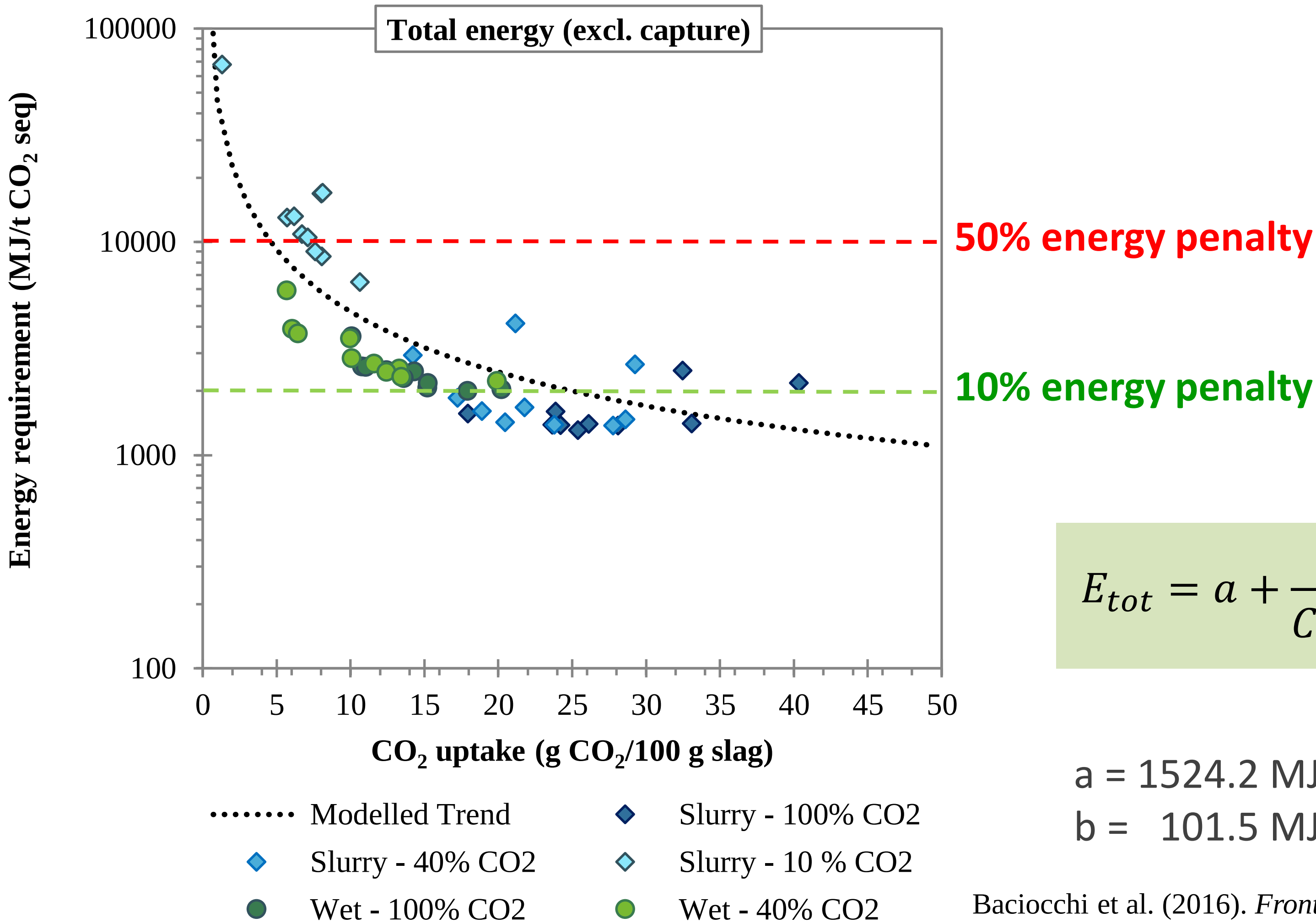
Several studies have addressed the issue of the energy penalties associated to carbonation processes in view of the assessment of the feasibility of their application at full scale

	MATERIALS	ROUTE	PENALTIES
ALBANY RESEARCH CENTER (2005)	• Minerals	Slurry Phase	28 %
HUIJGENS ET AL. (2006)	• Minerals • Steel Slags	Slurry Phase	25 % 31 %
KELLY ET AL. (2011)	• Minerals • Steel Slags	Slurry Phase	55-100 % > 100 %
KIRCHOFER ET AL. (2012)	• Minerals • Steel Slags, Coal Fly Ash • Cement Kiln Dust	Slurry Phase Slurry Phase Wet	25-75 % 34-45 % 14 %

- Large difference in the assumptions and in the resulting total energy penalties
- Lack of a specific wet route process layout

CO_2 uptake and energy requirements

➢ **Total energy requirement vs CO_2 uptake (excluding capture!!)**



$$E_{tot} = a + \frac{b}{{CO_2}_{upt}^{1.5}}$$

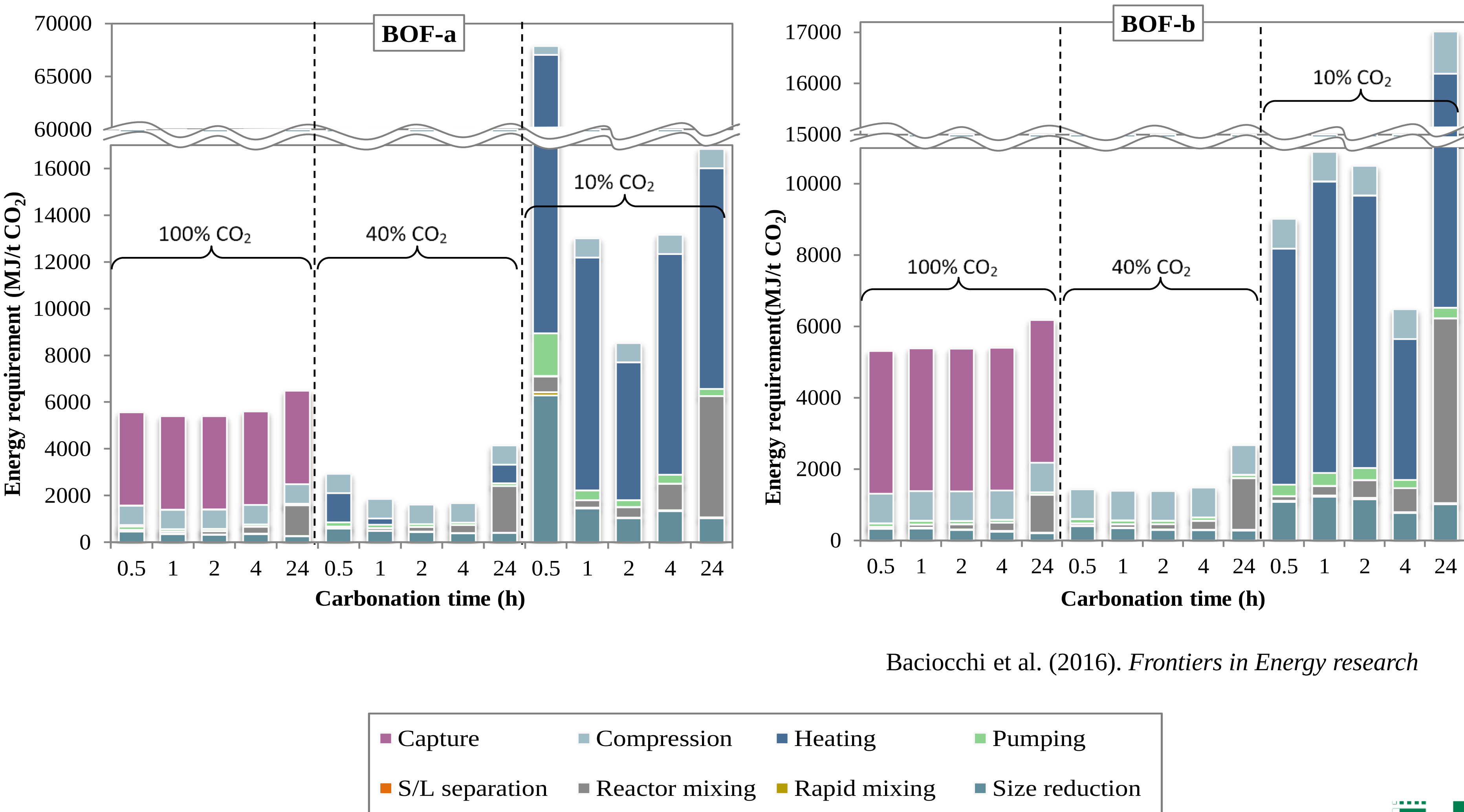
a = 1524.2 MJ/t_{CO2}

b = 101.5 $MJ\ t_{CO2}^{0.5}/t_{slag}^{1.5}$

Baciocchi et al. (2016). *Frontiers in Energy research*

Energy requirements for the Slurry Phase Route

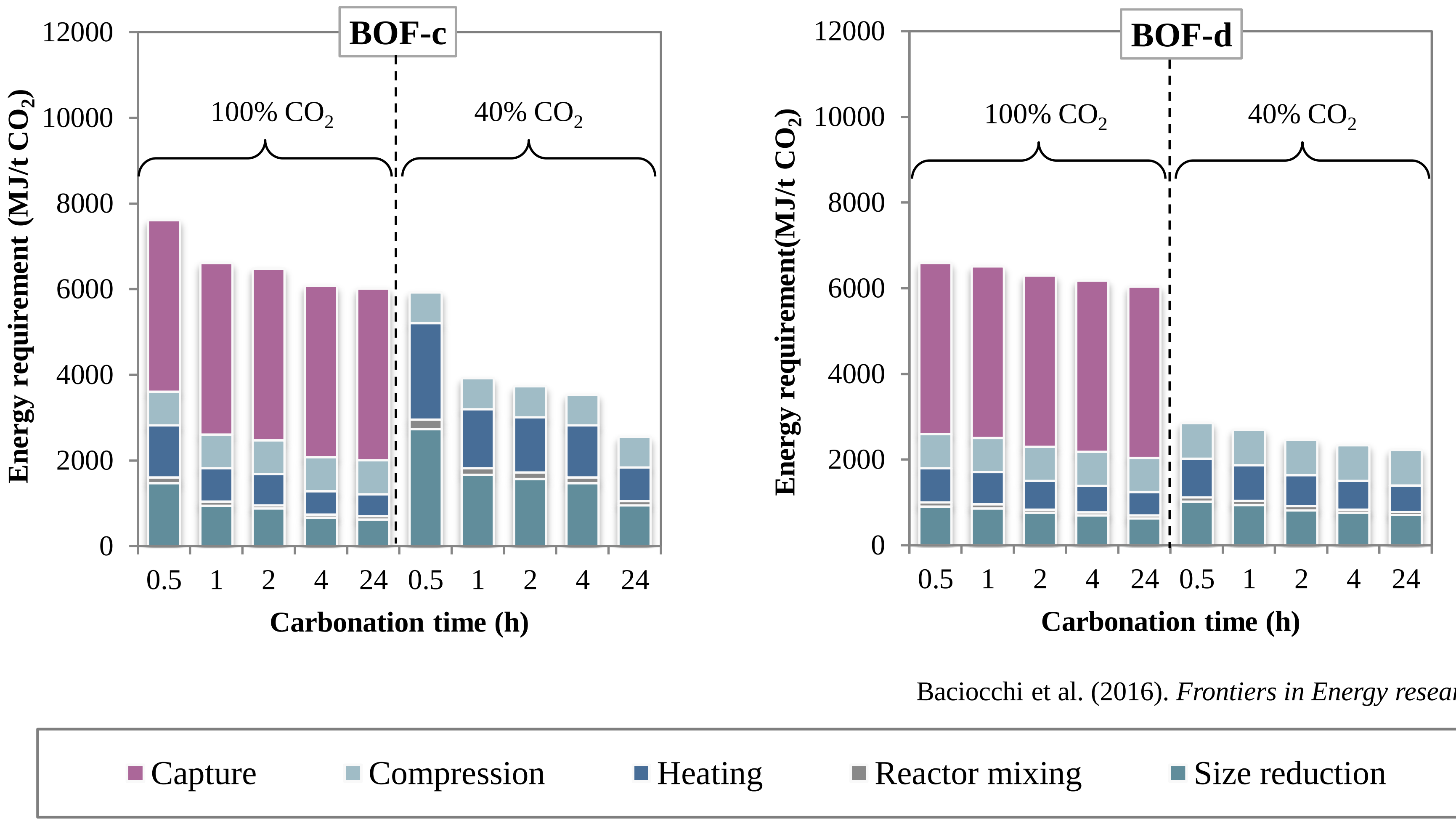
➢ Energy requirement of each unit operation



Baciocchi et al. (2016). *Frontiers in Energy research*

Energy requirements for the wet route

➢ **Energy requirement of each unit operation**



Baciocchi et al. (2016). *Frontiers in Energy research*

Feedback from MI workshop participants: open issues

- Low energy activation & enhanced feedstock reactivity under lean CO_2 conditions
- Complete or near to complete utilisation of mineral feedstock
- Optimization of passive carbon mineralization process
- Molecular-scale simulation of carbonation reactions
- Thermodynamic properties of alkaline minerals for geochemical modeling
- Reusable carbonation additives/reagents
- Making use of carbonation exothermic heat
- Synthetic minerals for carbonation
- In-situ monitoring of carbonation reactions
- Material Reactivity: Flue gas conditions material behavior, kinetics enhancement, pre-treatment options
- Process integration: Energetic modeling, cost modeling
- Cost effective catalytic enhancement of dissolution, separation and carbonation of silicate materials (ligands, CA, seeding, etc.)
- Innovative system integration for recycle and reuse of energy (heat) and materials

Feedback from MI workshop participants: open issues

- Combining various industrial waste materials for CO_2 carbonation technology (i.e. producing $NaHCO_3$ from desalination waste water)
- Role of the curing step on extent of carbonation and products' properties (e.g. in situ measurements, carbonation tests with model mineralogical phases)
- Scale up issues and data for LCA. Standardization of CO_2 life cycle analysis for carbonation processes
- Effects of operating conditions on the leaching behaviour of the product & solutions for reducing mobility of specific elements (metalloids) after carbonation
- New MC-based pathways for the transition to a circular economy of construction materials
- Innovative MC-based mining & mineral processing pathways for base metals production
- Breakthrough MC-based production of energy carriers
- Dry or low water consuming MC processes

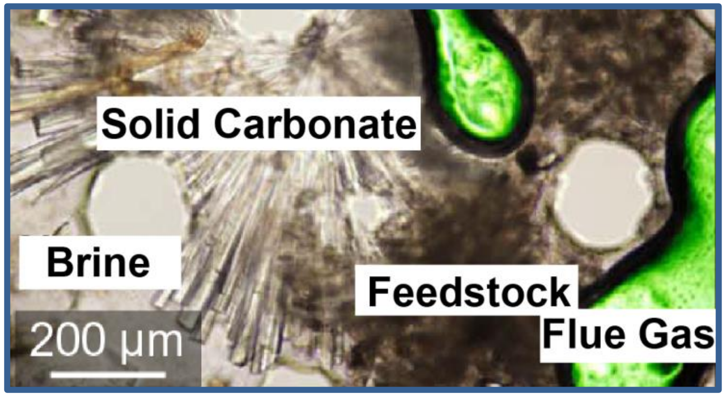
Feedback from MI workshop participants: open issues

- Effect of further water curing after CO_2 curing on the hydration products and microstructure of CO_2-cured concrete
- Effect of carbonated recycled aggregate on the properties and microstructure of recycled aggregate concrete
- Evolution of different carbonation product-layers (calcium silicates, lime, calcium hydroxide and C-S-H gel) and diffusion mechanism of gas and ions through the layer
- Restructure process of cementitious system during carbonation in the bulk solid phase
- Nucleation and growth mechanisms for carbonation/de-carbonation
- High CO_2 density precursors for *in situ* carbonation
- Ultra-fast carbonation
- Cheap CO_2 sources
- Creating realistic time-lines for technology adoption and creating a climate model that evaluates its effectiveness

PRD 1: Accelerating carbon mineralization by exploiting the complexity at solid-liquid-gas interfaces

• Scientific Challenges

- ✓ Carbon mineralization, a slow phenomenon, has been observed to proceed at rates orders of magnitude faster than predicted by conventional models.
- ✓ Predicting the dynamic speciation and product properties of solid feedstock/fluid/CO_2 systems is the key to unlock carbon mineralization to control reaction pathways and rates.



Microfluidics carbon mineralization experiment (after Harrison et al., 2017. Chem. Geol.)

• Research Directions

- ✓ Broad-spectrum collection of thermodynamic and kinetic data associated with carbon mineralization of feedstocks, focusing on reactions and mass transfer at solid-fluid interfaces.
- ✓ Development of broadly available on-line high-resolution investigative tools for local mass transfer measurements and phase characterization.
- ✓ Mechanistic understanding and predictive phenomenological modelling of carbon mineralization processes at the molecular level.

• Impacts

- ✓ Fast-tracked novel market ready net positive energy carbon mineralization processes for permanent CO_2 binding.
- ✓ Provide a ranked list of high potential carbon mineralization feedstocks.

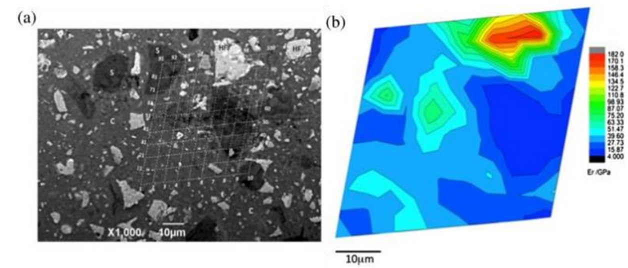
- ✓ Provide internally-consistent and validated thermodynamic, transport and kinetic data for carbon mineralization systems.
- ✓ Improved understanding of solid-liquid-CO_2 reaction pathways under a broad range of conditions.

PRD 2: Tailoring material properties to enable carbon storage in products

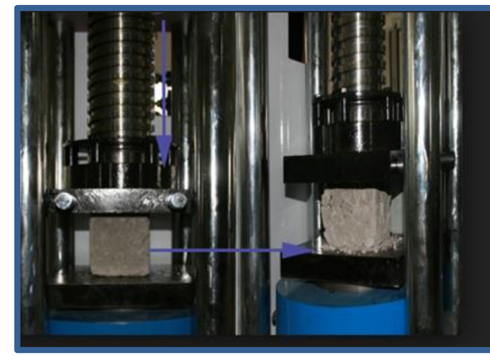
- ## Scientific Challenges
  - ✓ To realize the potential of carbon mineralization for the built environment we must predict and control processes to consistently meet product performance criteria.
  - ✓ Linking product performance to micro-structure, geochemistry and mineralogy is the key to achieve consistency.

- ## Research Directions
  - ✓ Develop and apply real time monitoring of carbon mineralization product properties during reaction.
  - ✓ Exploit nano-characterization for deriving insight into solid and aqueous speciation and improve control on bulk physical and chemical properties.
  - ✓ Understand and model structure-property-performance relationships.
  - ✓ Develop pre/post processing treatments to improve product performance criteria.
  - ✓ Predict and control long term durability for applications.

- ## Impacts
  - ✓ Reliable cost-effective processes for generating construction materials that meet performance criteria while permanently storing CO_2 on a Gigaton scale.
  - ✓ Provide a better understanding of process conditions on product properties (e.g. strength, leaching and durability).
  - ✓ Insights applicable to the carbonation of industrial waste streams and sub-surface mineral trapping.



Nano-indentation grid testing
(Mo et al., *Cement and Concrete Research*, 2016)



Carbonated building block performance testing
(Columbia Dept. of Civil Engineering)

Concrete forest (The Who's Who in *Building & Construction*, Houston Spring 2016 Ed.)

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