Task 19: Reactive Flow-Through Experiments: A Look at Foamed and CO_2 Resistant Cements

Project Number FE1022403

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US DOE/ NETL

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Technical Approach

Goal

- The objective of the effort is to investigate and evaluate the fracture opening or self-sealing of foamed cements and CO_2 resistant cements: Flow-through CO_2-saturated brine interactions at subsurface conditions typical in the Gulf of Mexico (GOM).

Research Questions

- Will foamed cements with a leak pathway (i.e. fracture) self-seal in a similar manner as ordinary Portland cement?
- When are CO_2-resistant cements needed?
  - Significantly more expensive than traditional Portland cements.
  - Not compatible with the traditional Portland cements used in other sections of the well.
- When can we use Portland cements and when should we use a specialized cement?
- These answers will improve safety, well integrity, and have significant economic benefits.

Approach

- It is unfeasible to run experiments on every single variable that exists in the subsurface. Therefore, the team needs to understand the fundamental mechanisms to make predictions.
- Flow-through experiments are being conducted on various cement formulations.

Current Research Scope

Samples

1. Generate foamed cement using API RP 10 B-4 procedures
   - Different foam qualities (20%, and 30% gas volume)
2. A commercially available CO_2-resistant cement
   - Fly Ash-modified Calcium Aluminate Phosphate Cement
3. Coal-derived Engineered Carbon
   - including graphene oxide, graphene flakes, coal-based graphene flakes, and coal-based carbon dots

Experiments

1. Cement cores fractured using the Brazilian method
2. Uniaxial Hasler cells with a confining pressure to create flow through the cement core
   - Predetermined flow rates for predetermined lengths of time.
   - Constant flow rate short core experiments
   - Constant pressure differential composite core experiments
3. CT- flow-through experiments

Current Research Scope

Analysis

1. Multi-scale computed tomography (CT) scanning*
    1. Resolution of 17 μm
2. Scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS)
3. ATR-FT-IR (Attenuated Total Reflectance-Fourier Transform Infrared Spectroscopy
4. Mechanical testing

Flow Through

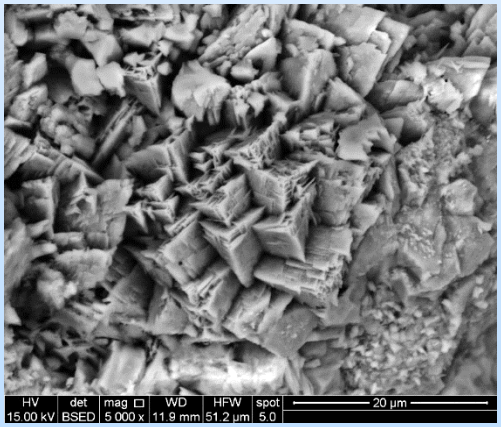
1. Confining pressure = 1200 PSI
2. Pore pressure = 800 PSI
3. DI water at equilibrium with CO_2 as injected fluid (room temperature)
4. Flow rate of 0.1 and 0.5 ml/min

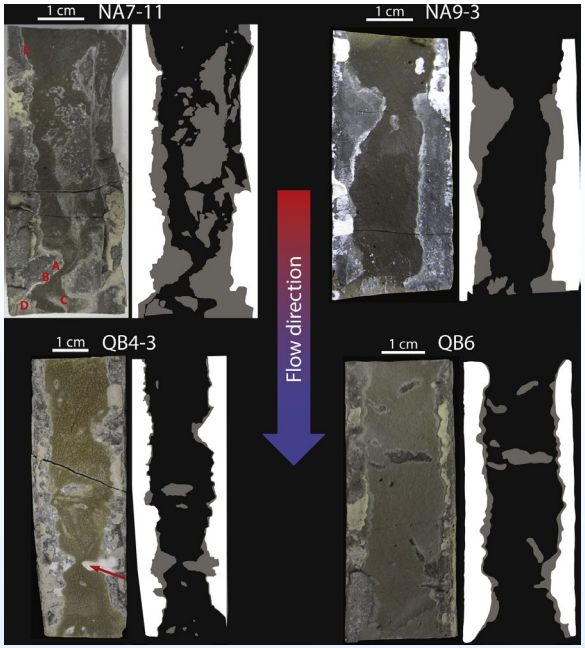
ImageJ Processing

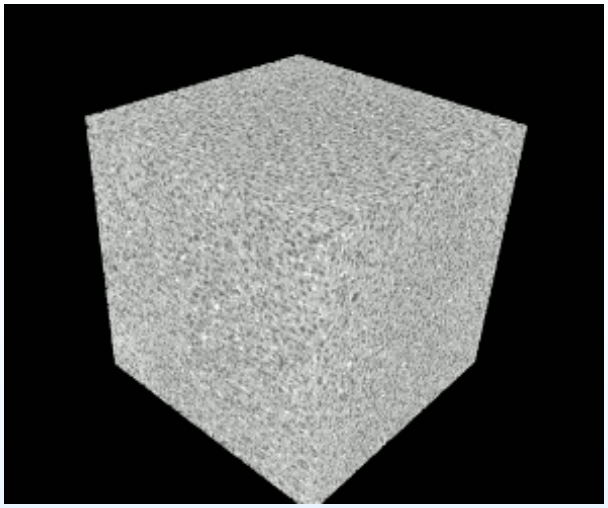
1. Images were scaled by 50% (reduction to 0.5 in X/Y/Z)
    a. Size management is critical to processing speed and efficiency
    b. Images underwent bright outlier removal at 2-pixel radius
2. Images were then filtered using 2x2 mean (3-D)
    a. Processes facilitated easier segmentation & feature isolation

Project Schedule

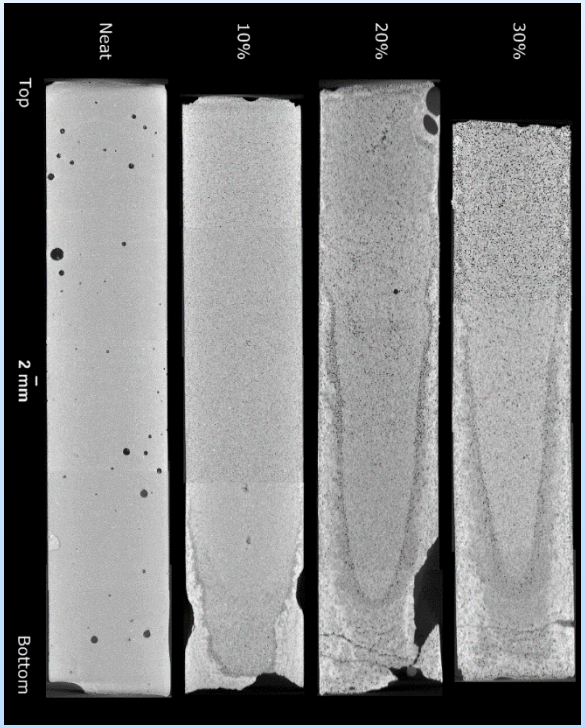
- Milestone: Identify key mineral and chemical alterations of Class H foamed cement exposed to CO_2 and fluid. 12/2019 - Completed
- Milestone: Determine if fractured Class H foamed cement is capable of self-healing. 3/20/2020 Completed
- Milestone: Determine the effectiveness of CO_2-resistant cements versus traditional Portland cements (Class H). In Progress
- Milestone: Fluid Dynamics – numerical simulation of flow properties and cement behavior (see next slide)

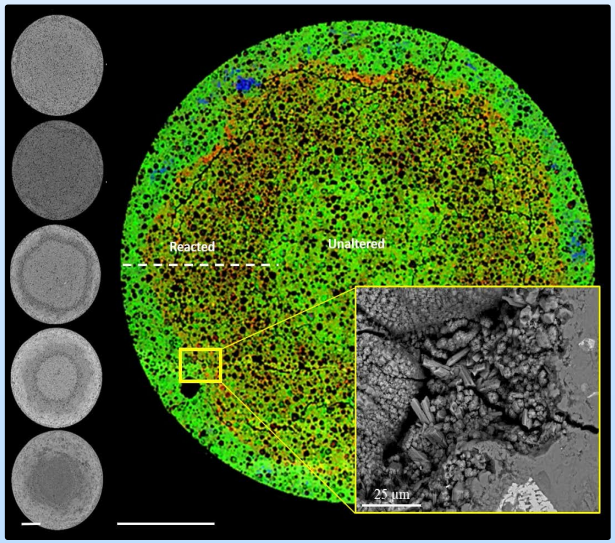



1 cm
NA7-11
1 cm
NA9-3
Flow direction
1 cm
QB4-3
1 cm
QB6



RESULTS


Neat
10%
20%
30%
Top
2 mm
Bottom


Reacted
Unaltered
25 µm

Ordinary Portland Cement (OPC)

Flow direction

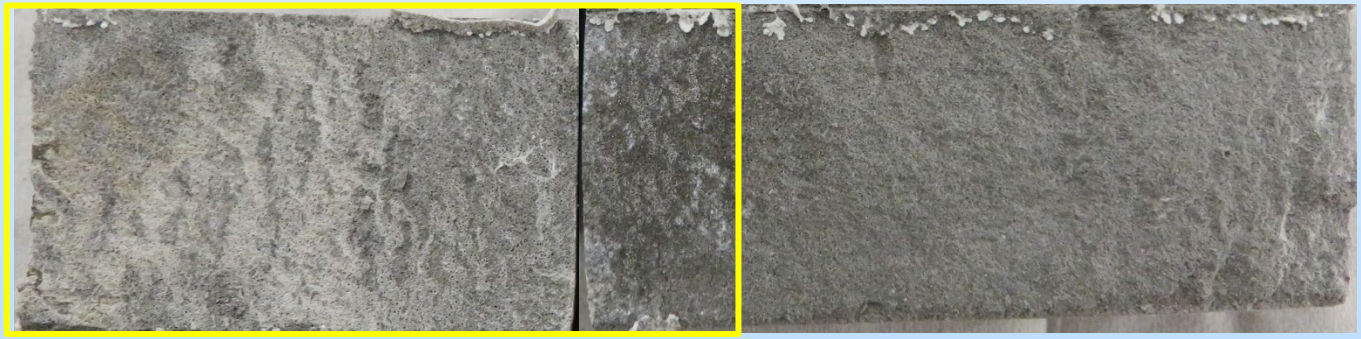
Sample A4

5.6cm,
0.03-0.2mL/min,
60mL fluid flowed,
0.18md to 0.03md

Most reaction happens within 5cm
Flow is channelized

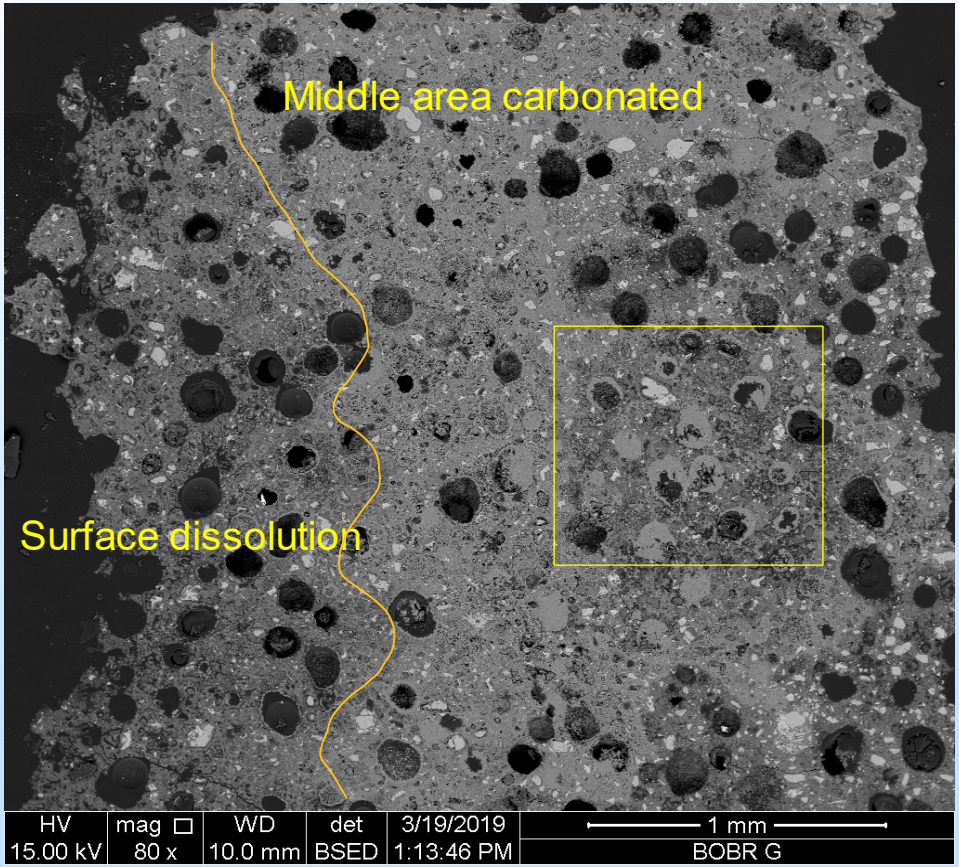
Sample A1

Sample A3

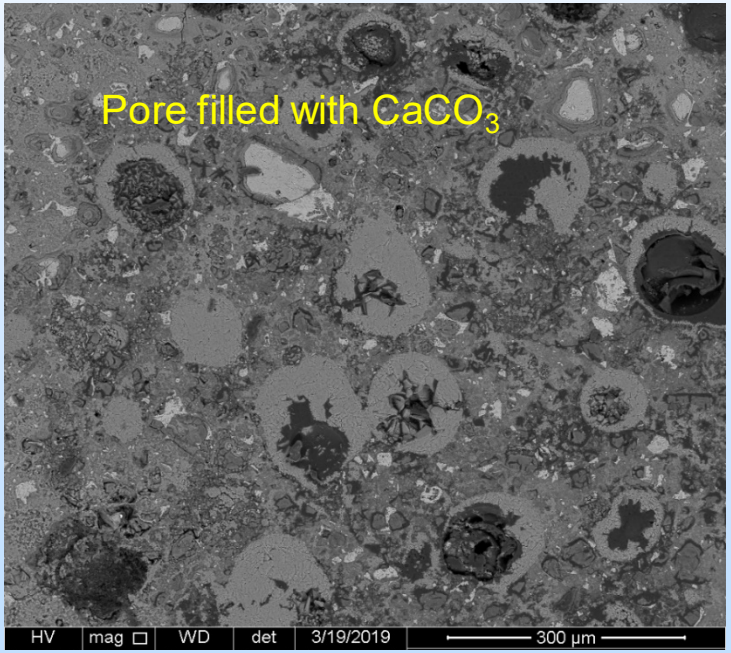


10.3cm,
0.05mL/min,
50mL fluid flowed,
0.17md to 0.10md

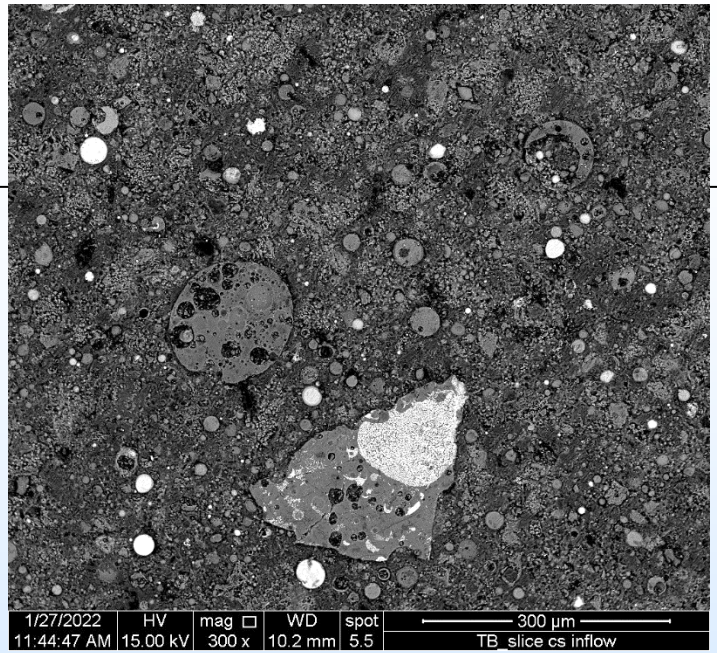
OPC cross section - Example

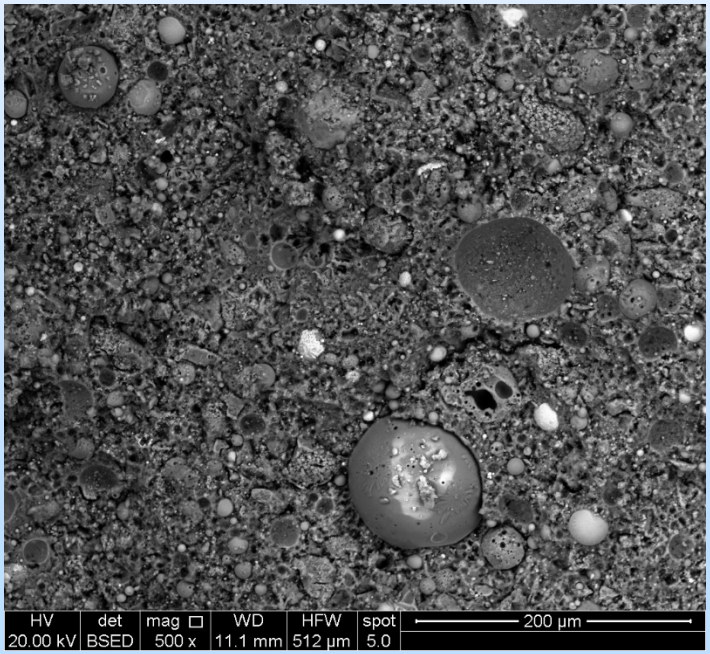


3mm at inlet



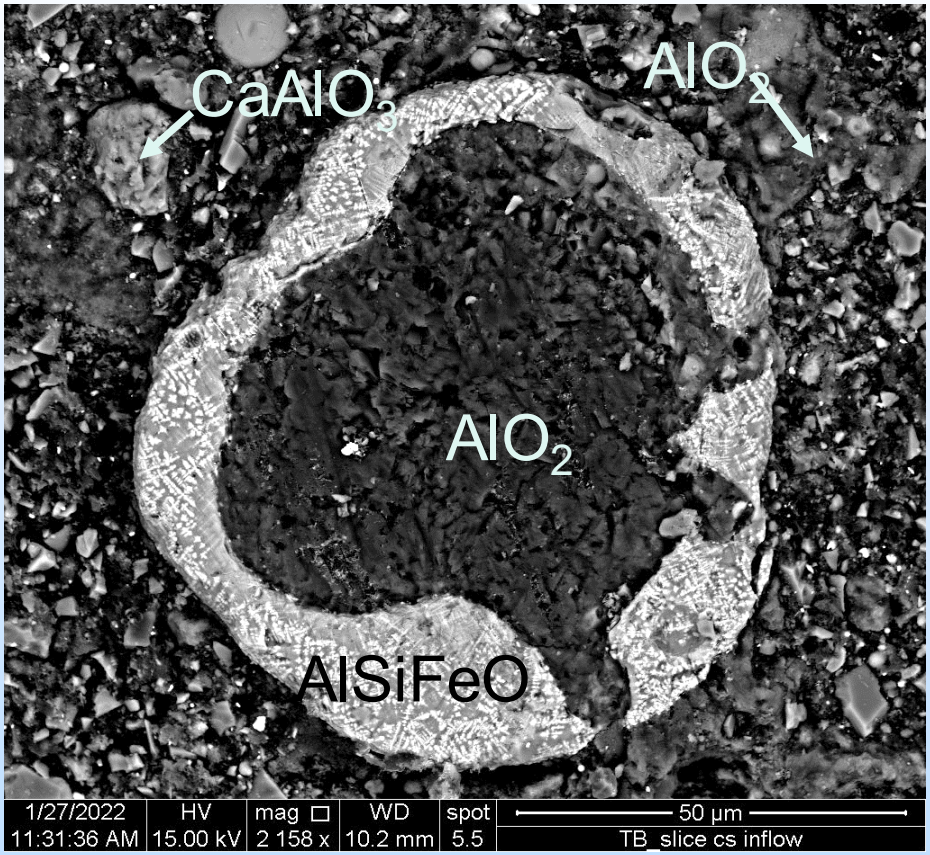
CO_2 Resistant Cement



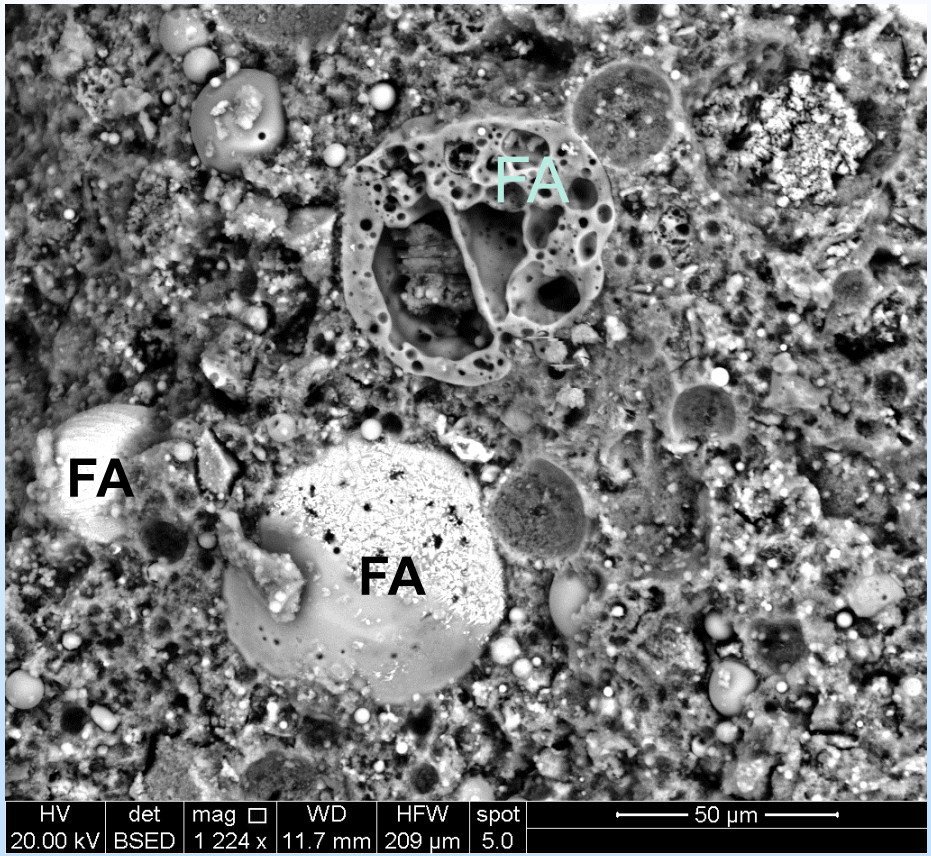


- Calcium aluminate
- Sodium polyphosphate
- Fly ash
- Non-crystalline additives

CO_2 Resistant Cement - unexposed



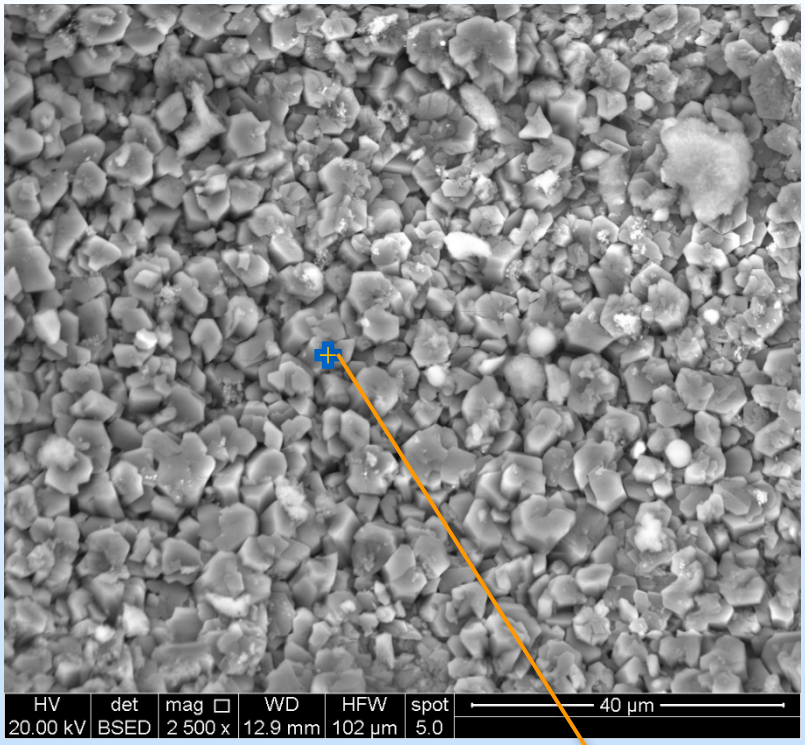
Polished cross-section

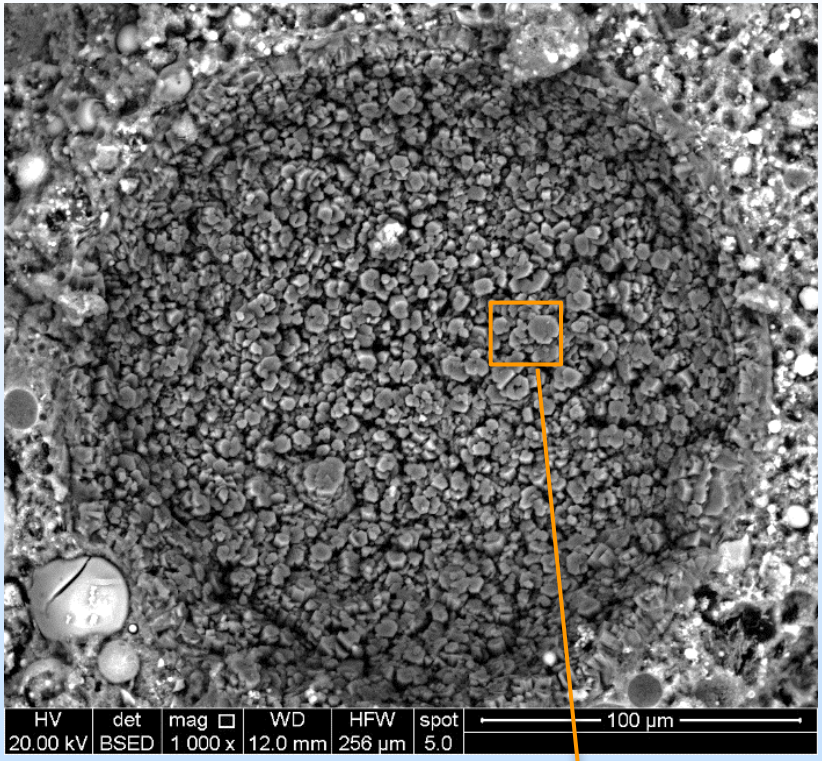


Fracture surface/unpolished

A lot of fly ash (Type F)

CO_2 Resistant Cement - unexposed





Spectrum 9

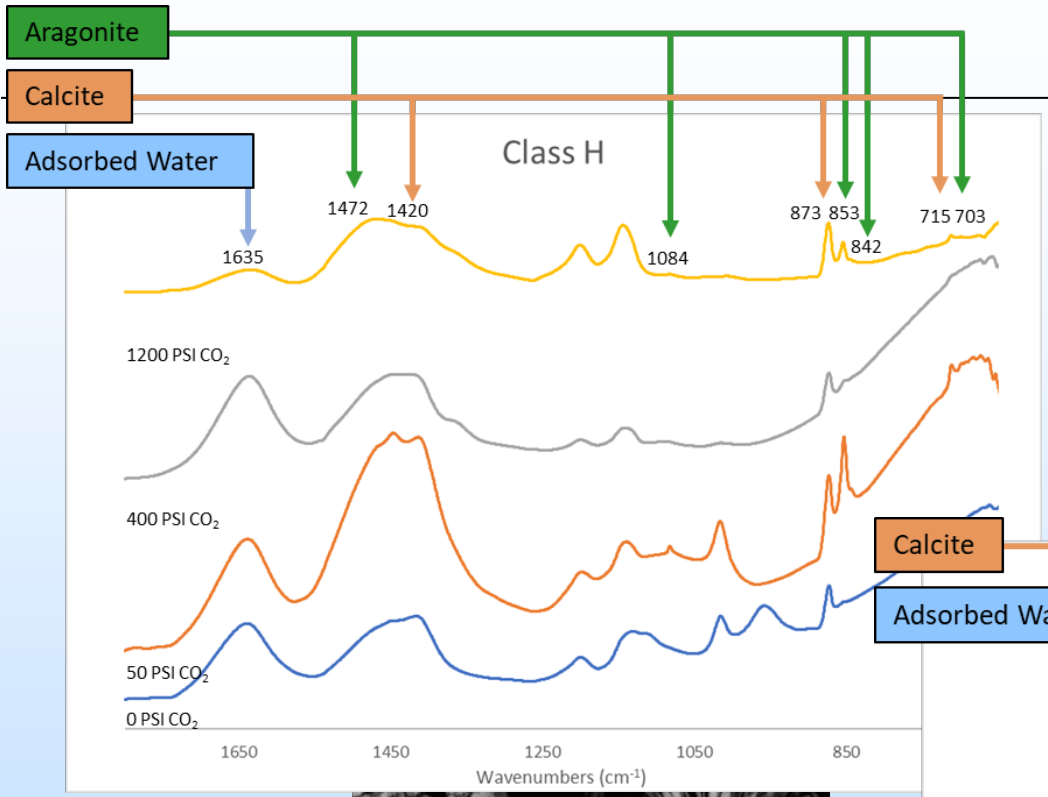
	Wt%	σ
O	63.0	0.5
Al	34.2	0.3
C	2.8	0.6

Spectrum 1

	Wt%	σ
O	60.6	0.6
Al	39.4	0.6

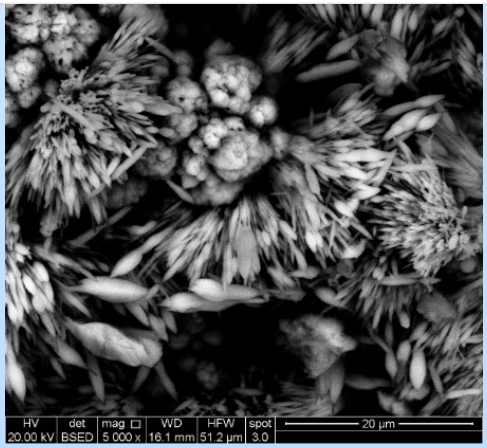
The voids are filled with an Aluminum-rich material – possibly Gibbsite

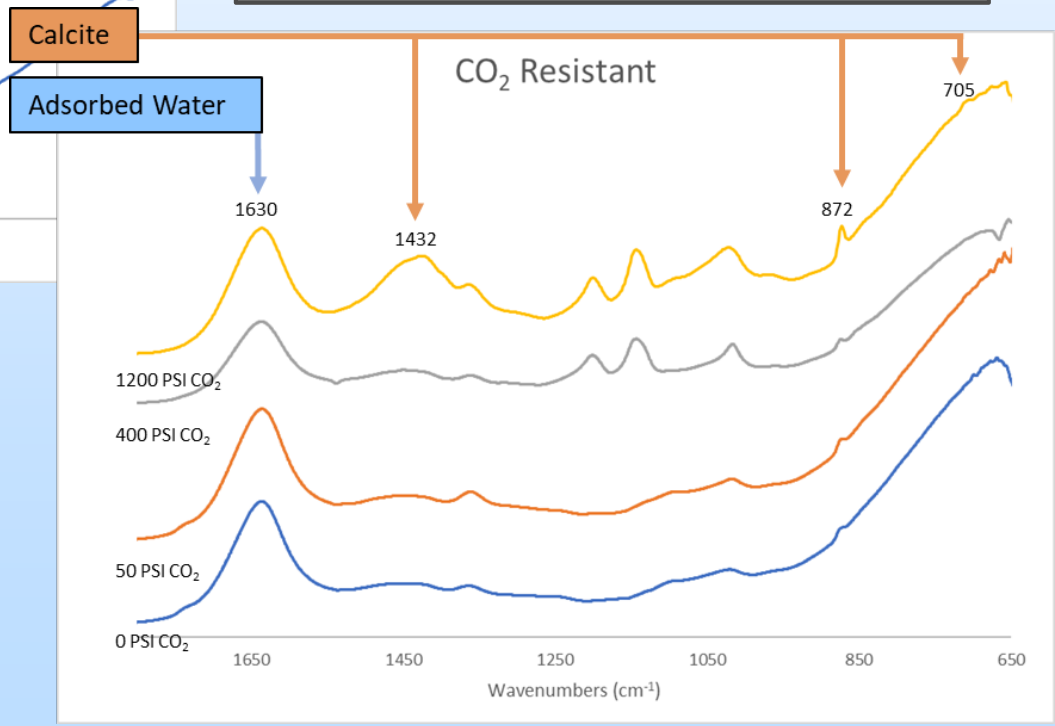
CO_2 Resistant Cement vs OPC: FT-IR



Class H cement shows pressure-dependent polymorphs of calcium carbonate

CO_2 resistant cement did not show changes in the calcite polymorph structure

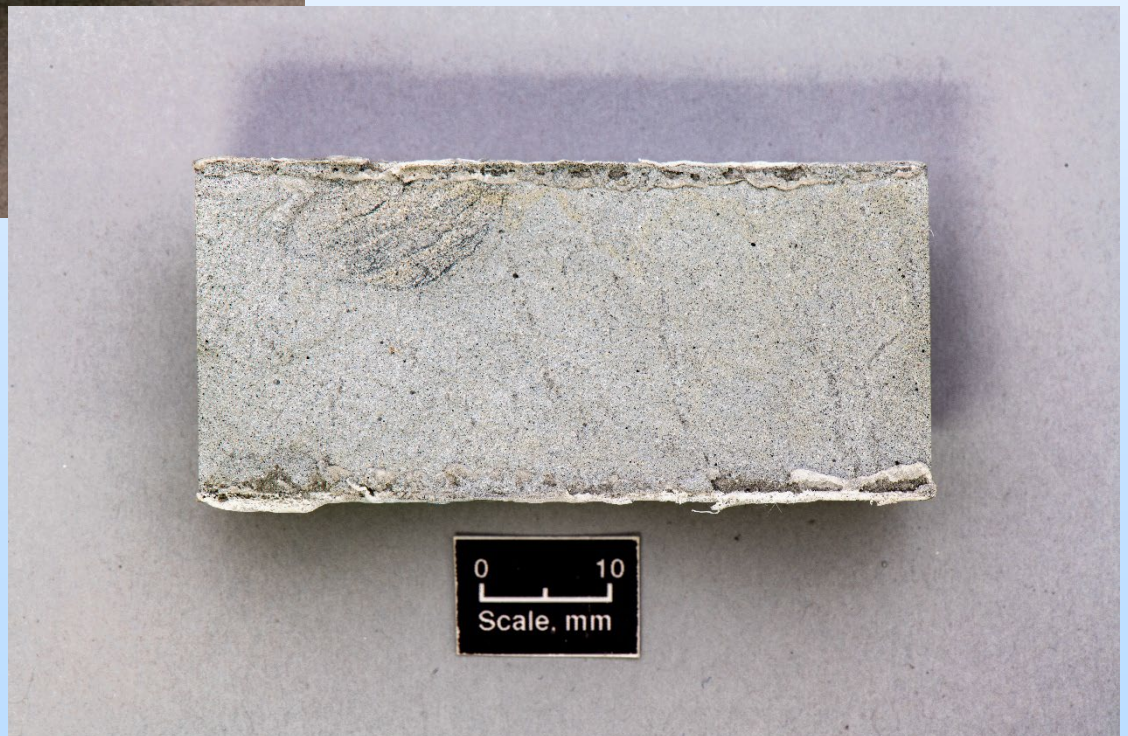




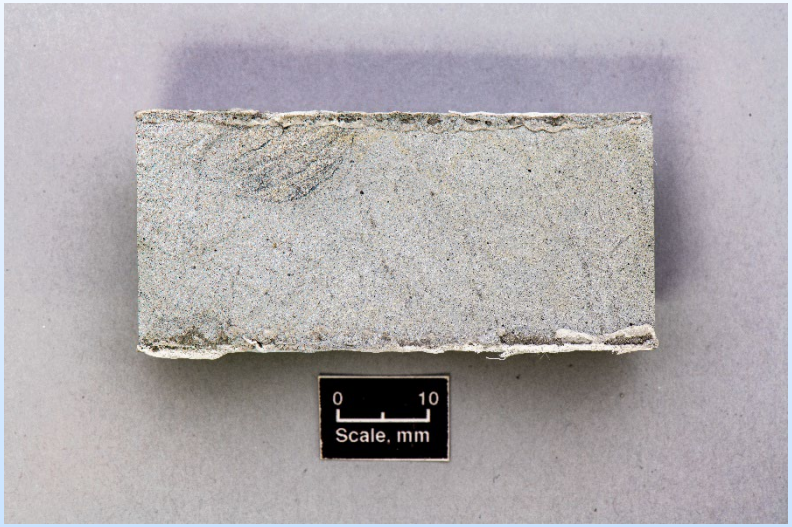
CO_2 Resistant Cement

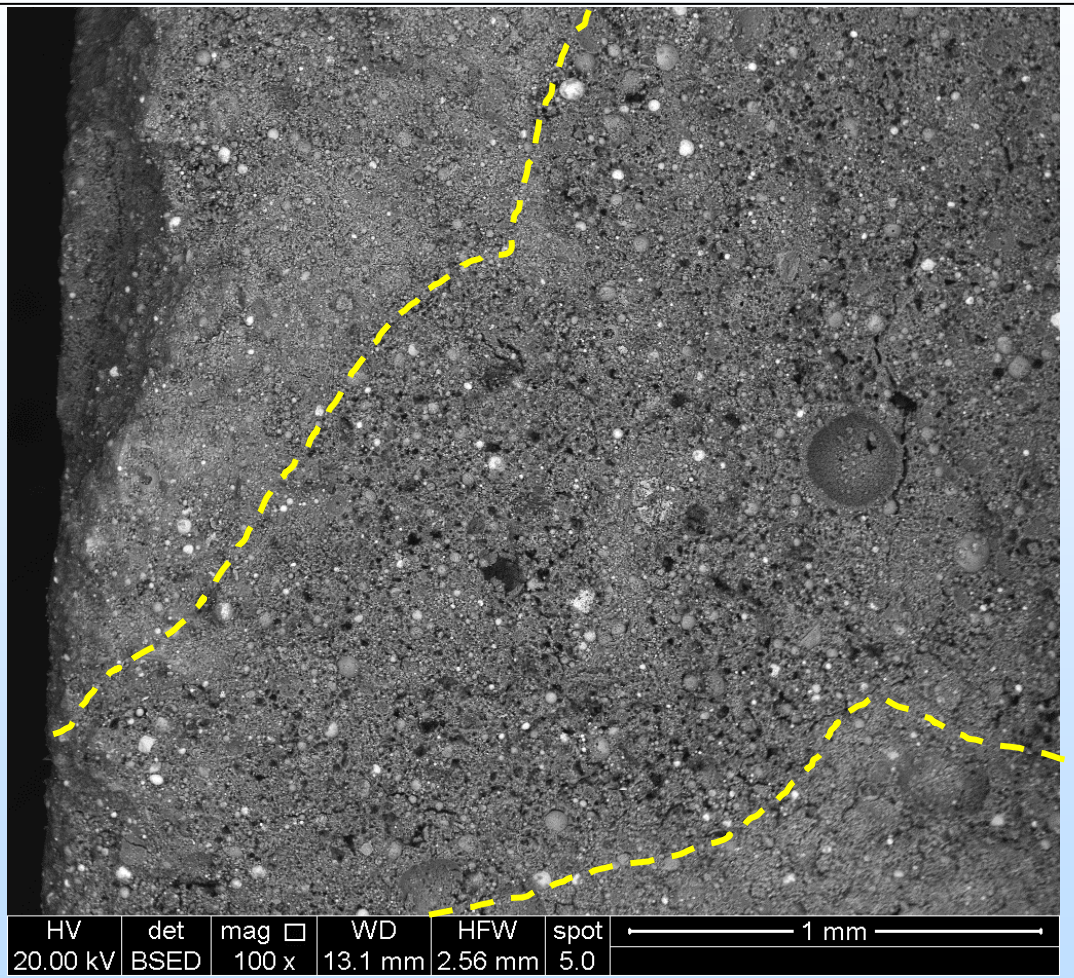
Unexposed

Exposed



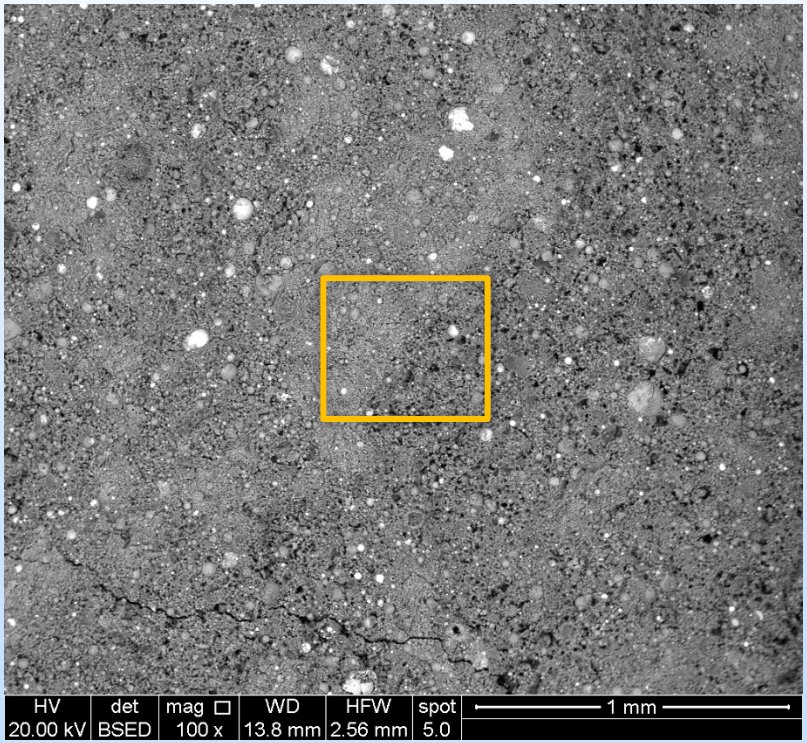
CO_2 Resistant Cement - exposed

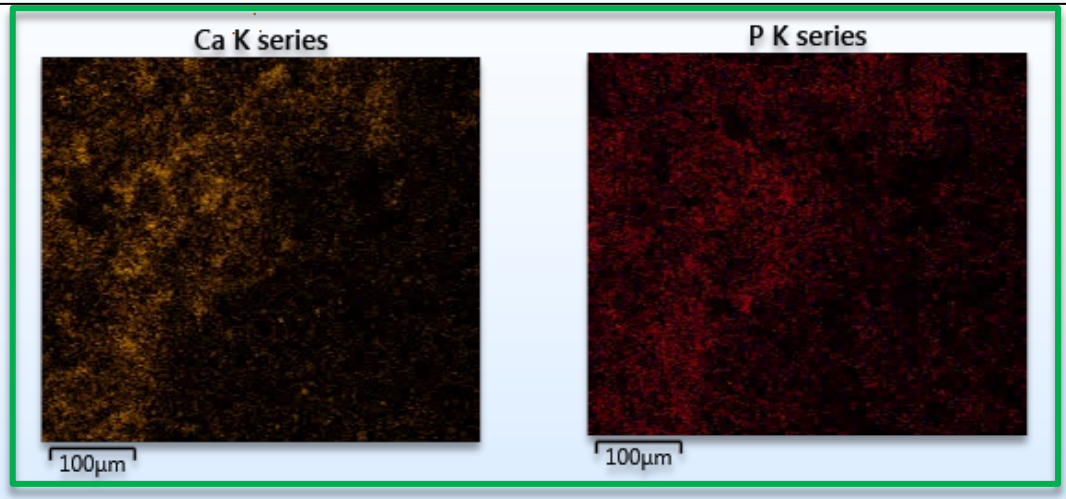


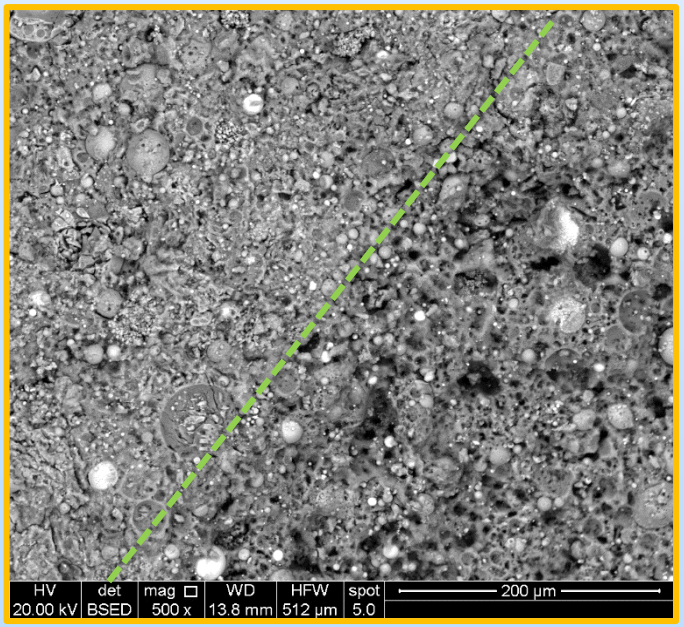


Slight alteration within yellow dotted lines

CO_2 Resistant Cement - exposed

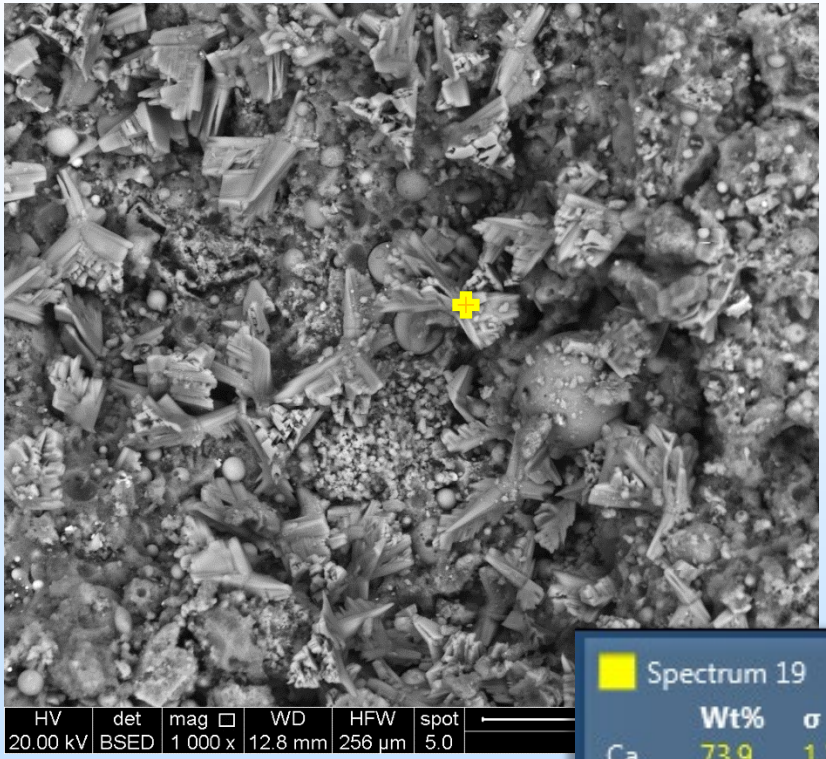






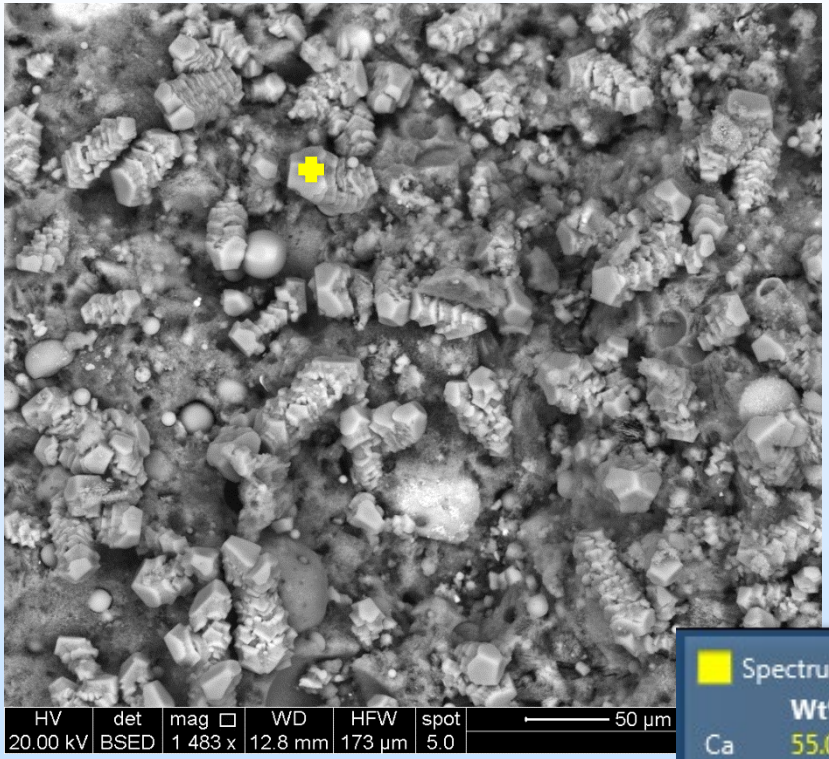
Calcium and Phosphorus show dissolution.

CO_2 Resistant Cement - exposed



Spectrum 19

	Wt%	σ
Ca	73.9	1.3
O	21.5	1.2
C	2.7	0.8
S	0.9	0.1
Al	0.6	0.1
Si	0.2	0.1
K	0.1	0.1



Spectrum 21

	Wt%	σ
Ca	55.0	1.2
O	37.4	1.2
C	5.8	1.3
S	0.9	0.1
Sr	0.4	0.3
Al	0.3	0.1
Si	0.1	0.1
K	0.1	0.1

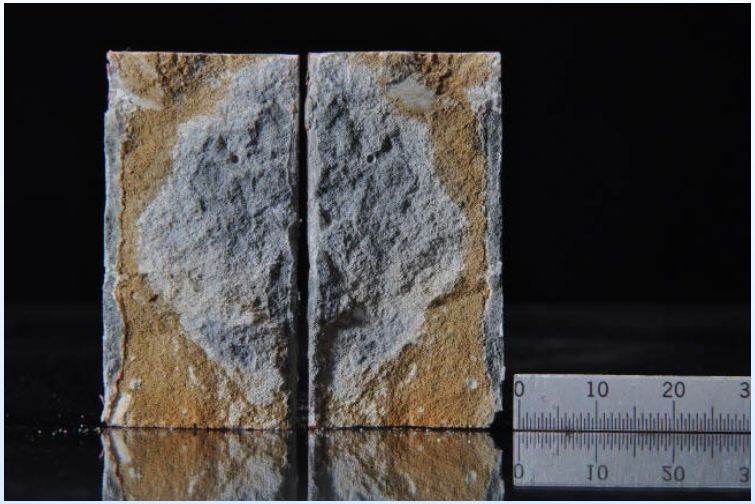
Summary

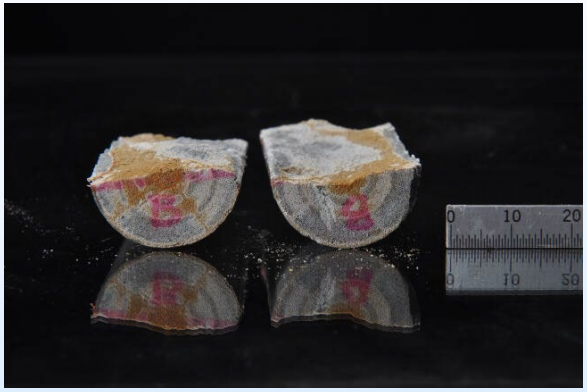
- Results showed that Portland Cements (both foamed cements and neat unfoamed cement) can self-heal with certain aperture sizes (milestones #1 and #2)
  - The extent of self-healing in foamed cements is comparable to that of neat cement.
  - This observation supports the hypothesis that applying foamed cement in deep water wells will not increase the risks of CO_2 leakage.
- CO_2-resistant cements do not show significant chemical alteration
  - We don't see the traditional dissolution and precipitation that we see in Portland Cements
  - Good for intact cement but might not be good for fractured cement where the chemical alteration is needed to ensure self-healing
- Waiting for flow data and mechanical measurements

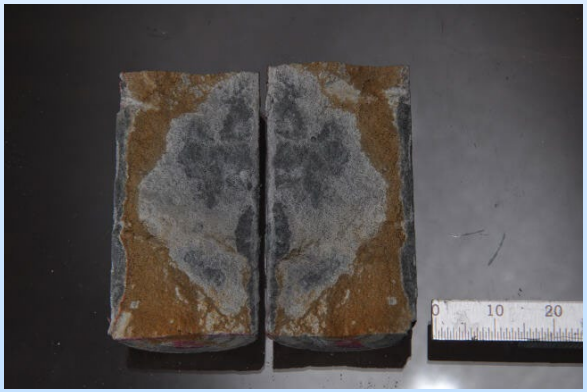
Questions?

Additional Information

Ordinary Portland Cement

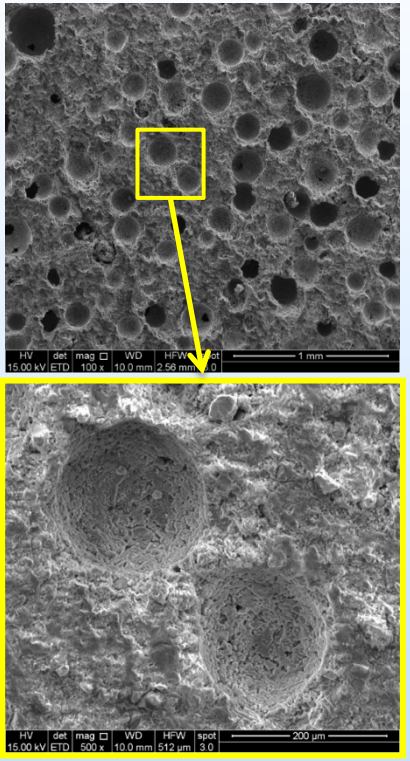




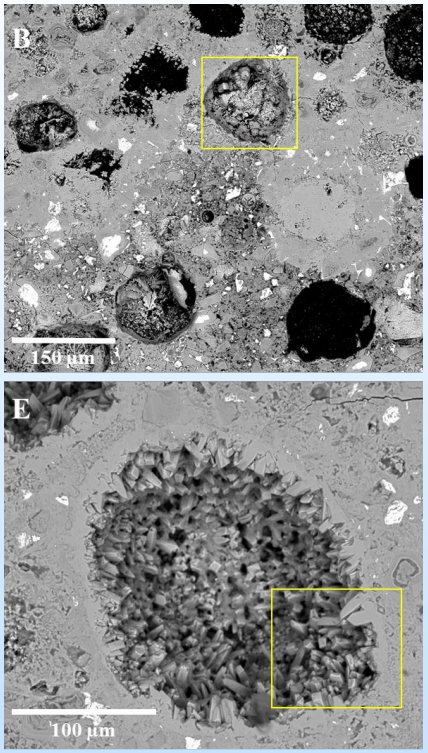


Photos of foamed cement sample (20% foam quality) exposed to variable flow of saturated CO_2 in the medical CT scanner

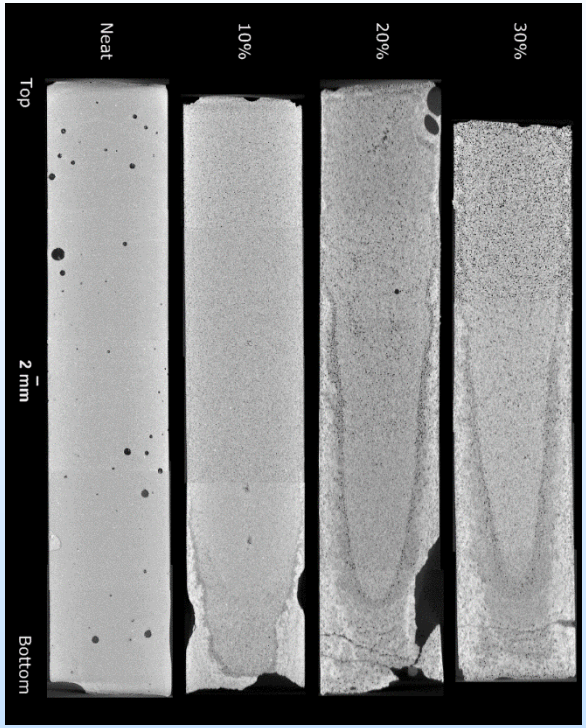
Previous Research



Unexposed foamed cement



Foamed cement exposed to $SCCO_2$ under static conditions (56 days)



Stitched CT Core montage on the XZ direction for neat, 10%, 20% and 30% cores exposed for 6 months. Stitched from approximately 9,000 2D images associated with the full scan of the core

The bubbles in the alteration zone are filled with calcium carbonate crystals

Illustrates how carbonation alters pore space by precipitation