The University of Texas at San Antonio™

Nanoparticle-Enabled CO_2 Foaming

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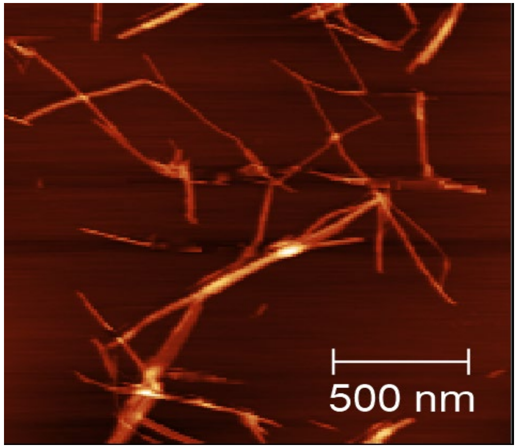
2025 INDUSTRIAL PROCESS EMISSIONS REDUCTION (IPER)
JANUARY 29, 2025

Nanoparticle Stabilized Foams

Cellulose Nanocrystals



- Isolated from plants, algae, bacteria
- Abundant
- Strong
- Limited toxicity
- Green material

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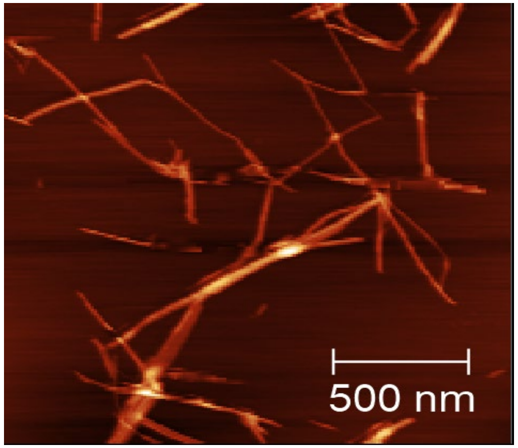

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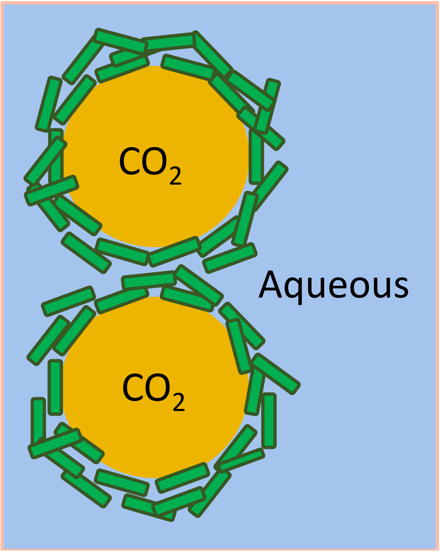

Pickering Emulsion

Foaming expected to lower CO_2 mobility and increase sweep efficiency in reservoir conditions

Nanoparticle Stabilized Foams

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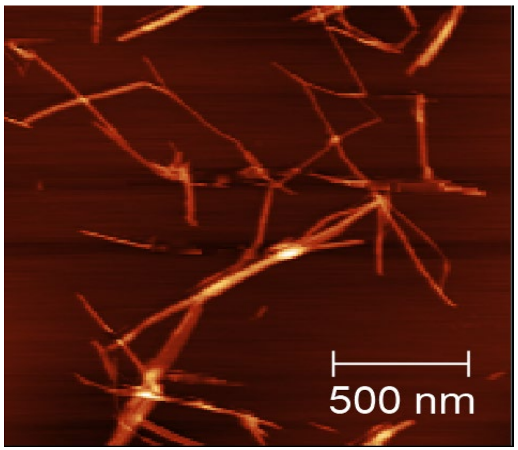

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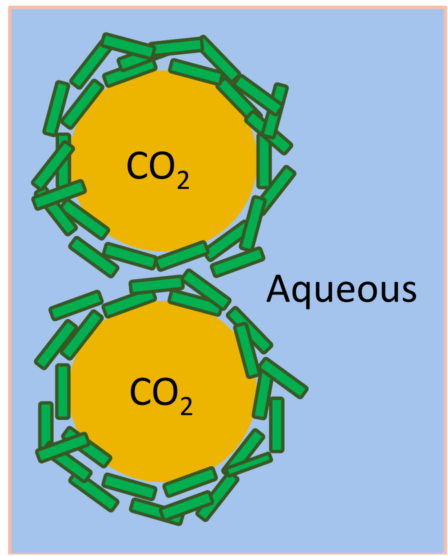
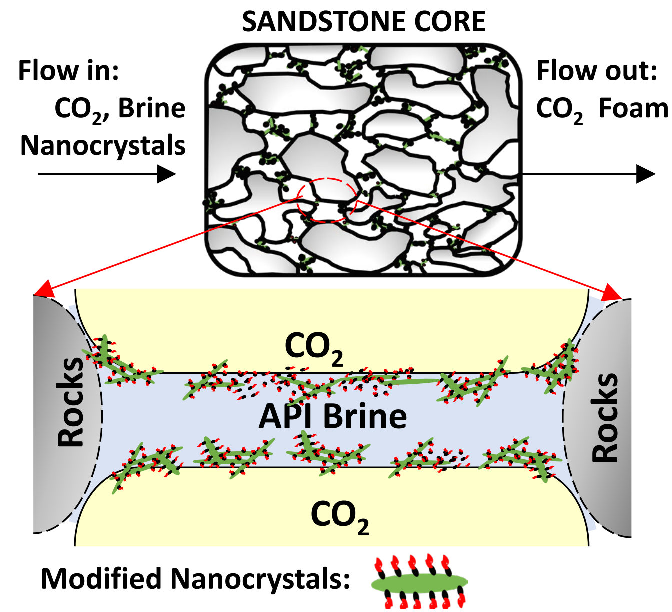


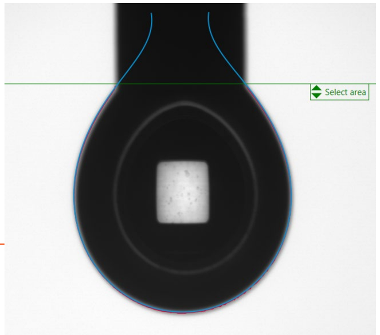
Pickering Emulsion

Transport

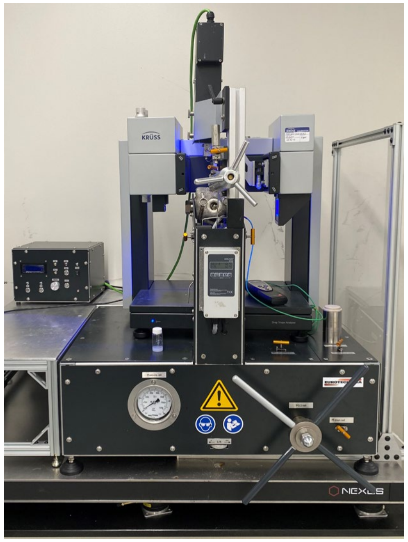


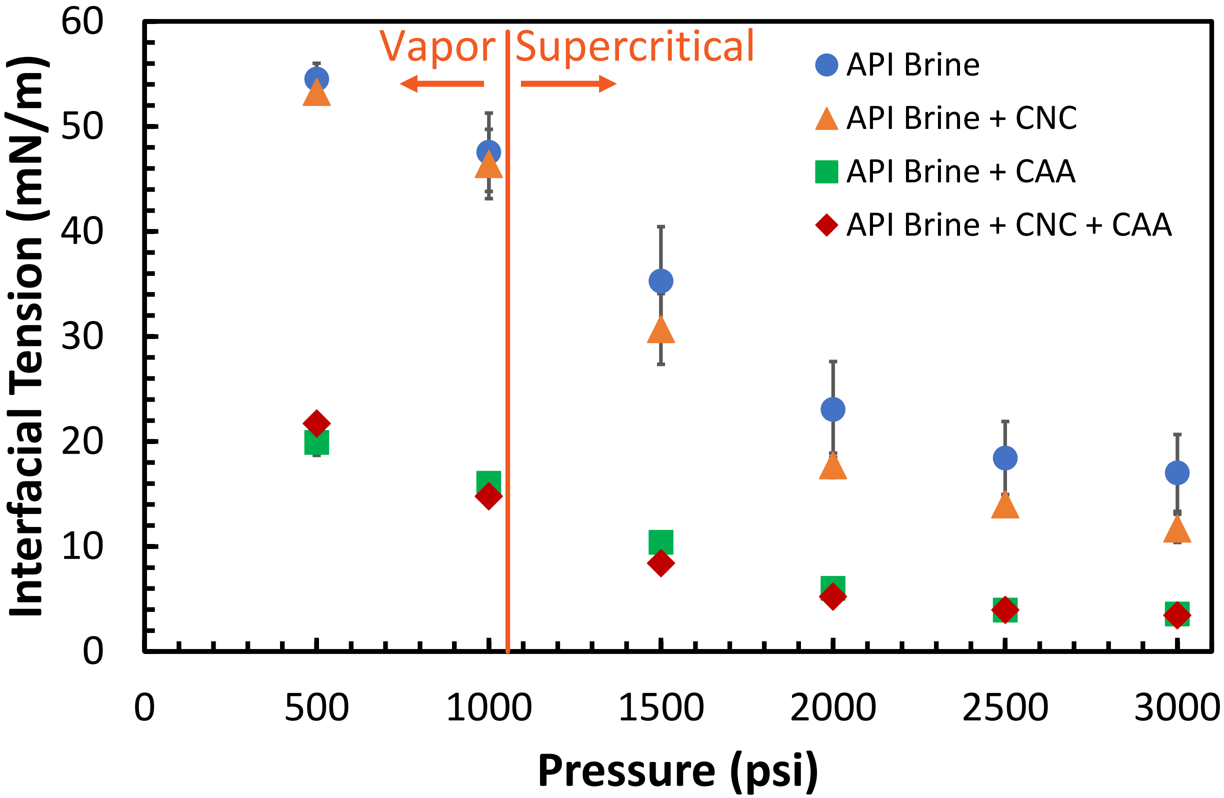
Foaming expected to lower CO_2 mobility and increase sweep efficiency in reservoir conditions

CO_2/Brine Interfacial Tension

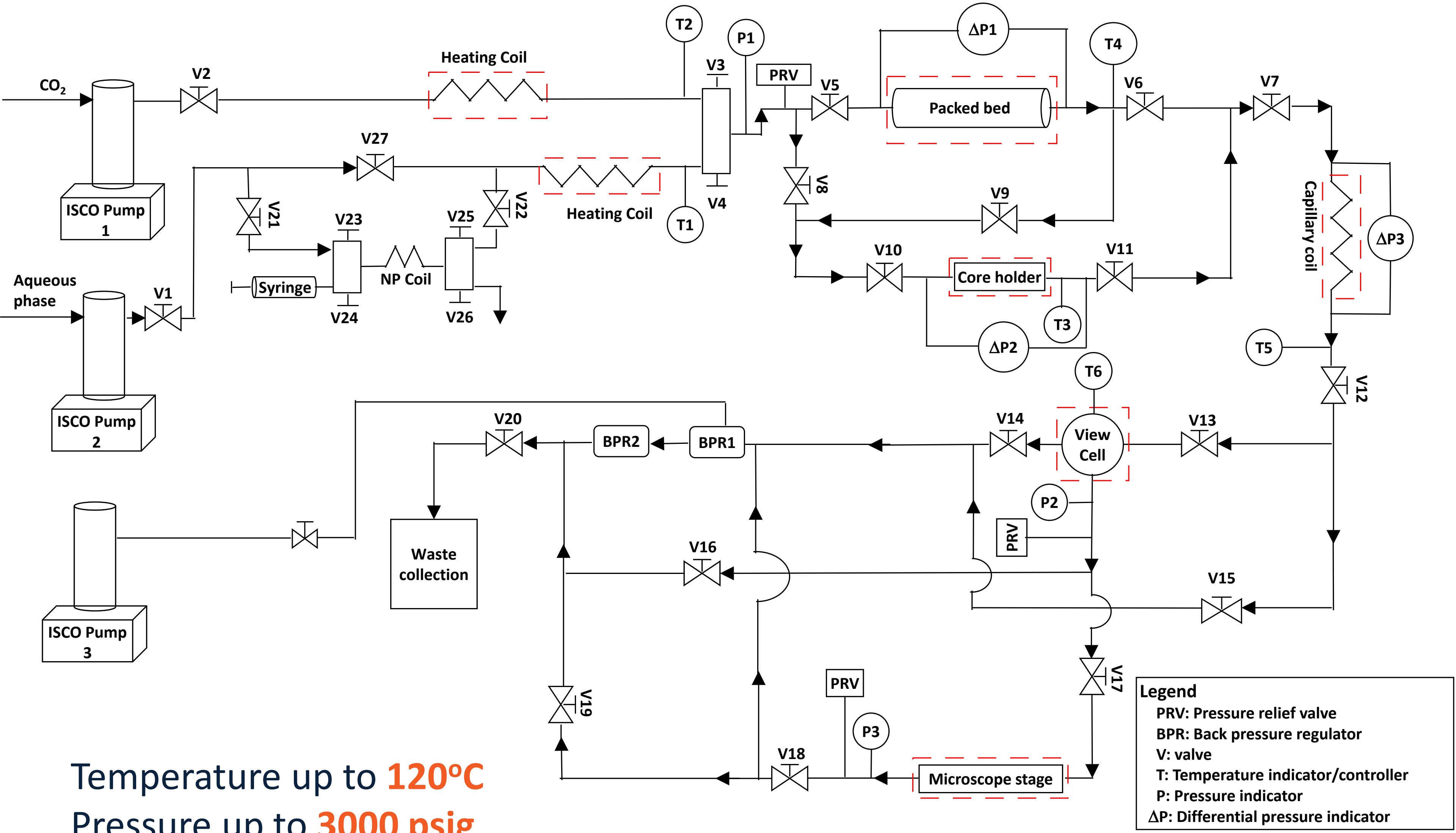


T = 60°C
CNC at 1.0 w/v %
CAA at 0.2 g/L
Brine:
- **2 wt% $CaCl_2$**
- **8 wt% NaCl**





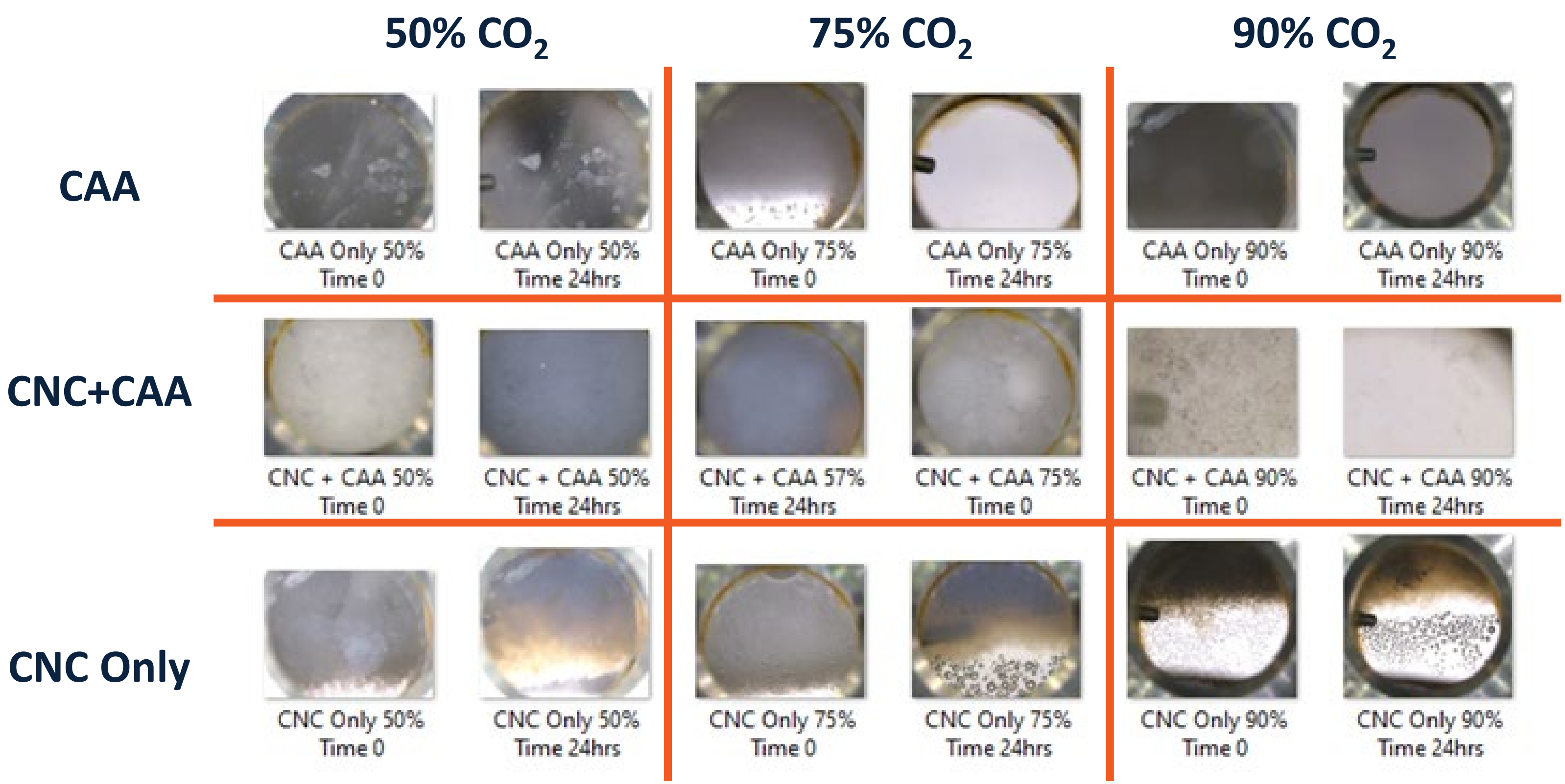
CO_2 Dispersions at Reservoir Conditions



Temperature up to **120ºC**

Pressure up to **3000 psig**

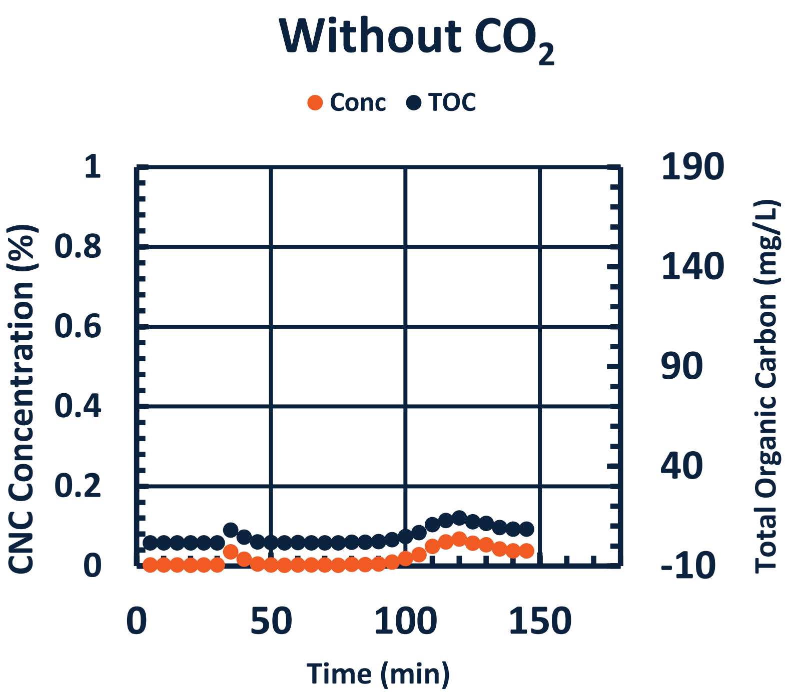
CO_2 Foams Stability

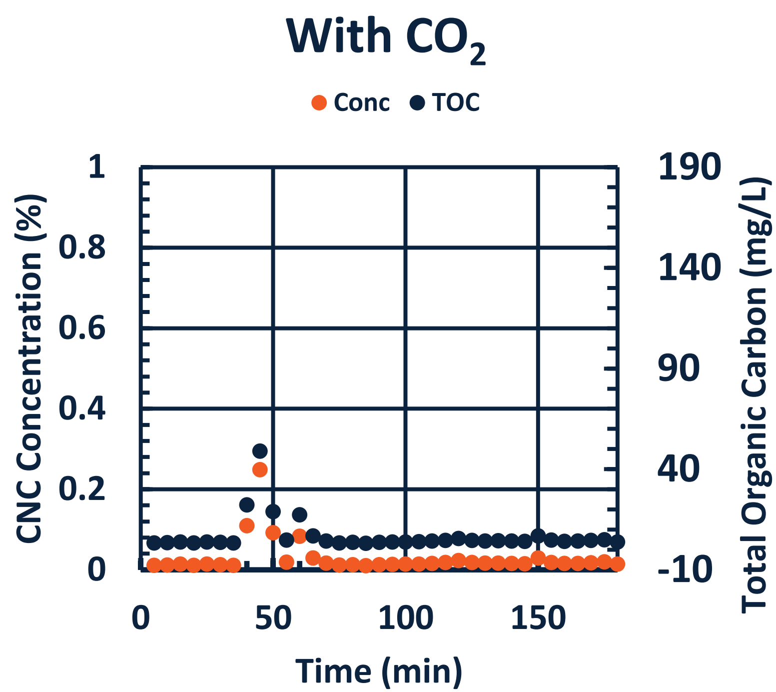


Temperature: **60°C**

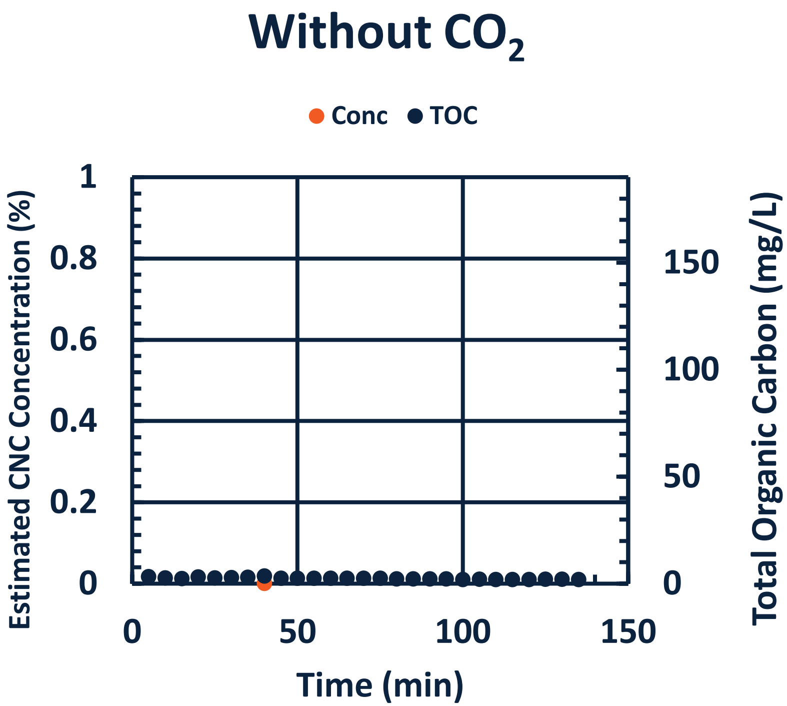
Pressure: **1500 psig**

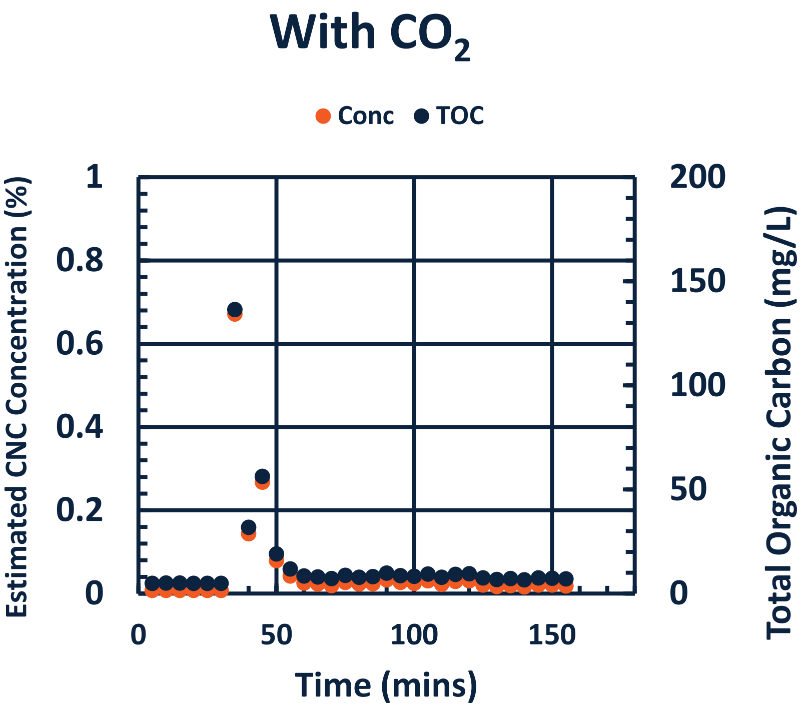
CNC Transport: Berea Sandstone





CNC+CAA Transport: Berea Sandstone





Summary

- CNC can stabilize supercritical CO_2 foams in reservoir conditions for at least 24 h.
- CAA addition lowers interfacial tension and increases CO_2 foam stability.
- CAA and the presence of a CO_2/brine interface enhances CNC transport through Berea Sandstone.

Acknowledgements

Postdocs


Graduate Students

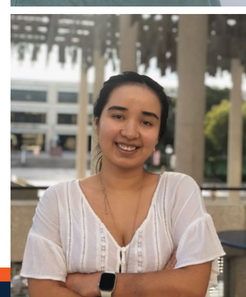
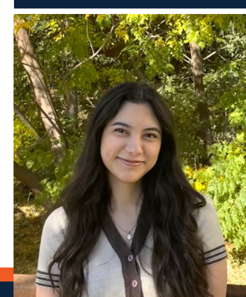


Undergraduate Students



Paige Law



ACS PRF

NSF

USDA

Thank you!!

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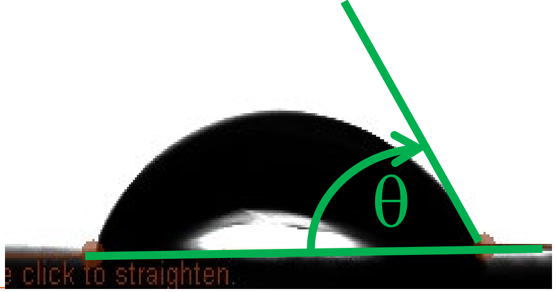
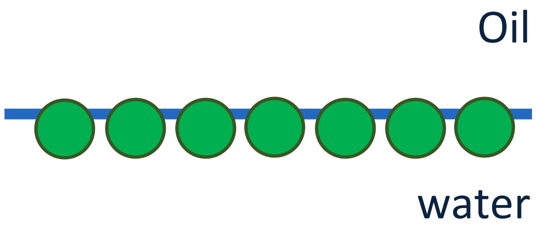
CNC Adsorption Energy at Dodecane/Brine Interface

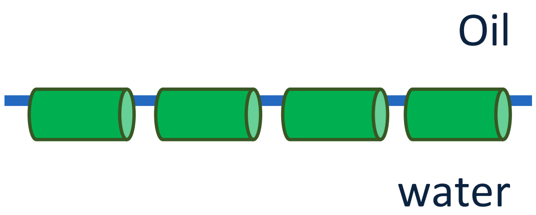


Spherical particles*



$$\Delta E_{sphere} = -\pi r^2 \gamma_{ow} (1 - cos\theta_{ow})^2$$

Rod shaped particles*

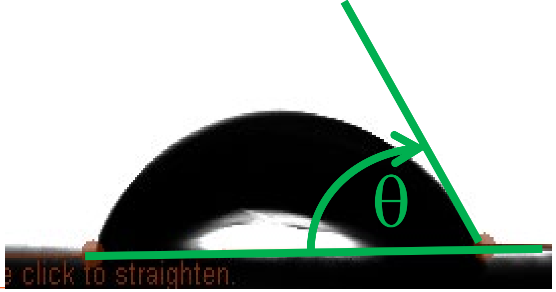


$$\Delta E_{rod} = 2rL\gamma_{ow}(\theta_{ow} \cos\theta_{ow} - \sin\theta_{ow}) + \gamma_{ow} r^2 \cos\theta_{ow} [2\theta_{ow} - \sin(2\theta_{ow})]$$

*Equations ignore particle-particle interactions

Parajuli, S. et al. *Langmuir* (2019) 35, 12061–12070.

CNC Adsorption Energy at Dodecane/Brine Interface



Gibbs energy of drop formation:*

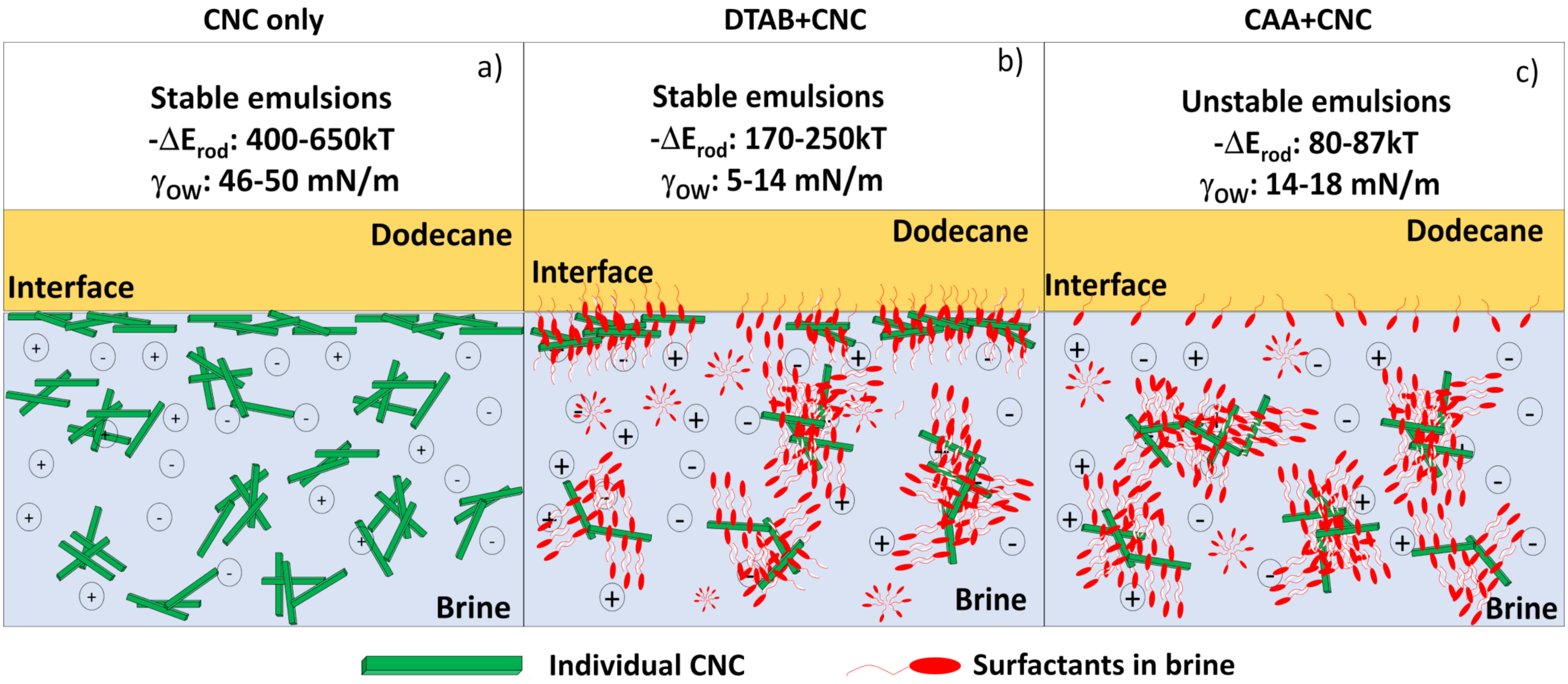
$$\Delta G \approx A_{ow}\gamma_{ow} + n_P \Delta E_{rod}$$

	API			SSW		
Surfactants	**θ_{ow} (°)**	**γ_{ow} (mN/m)**	**ΔE_{rod} (kT)**	**θ_{ow} (°)**	**γ_{ow} (mN/m)**	**ΔE_{rod} (kT)**
None	**28.2±2.0**	**49.5±0.8**	**-413**	**33.4±3.0**	**46.7±0.8**	**-643**
DTAB	**37.7±1.3**	**12.8±1.3**	**-253**	**42.0±2.1**	**6.3±1.6**	**-167**
CAA	**24.3±4.2**	**14.9±0.5**	**-80.2**	**23.8±1.2**	**16.7±1.1**	**-86.2**

*ignoring entropic terms

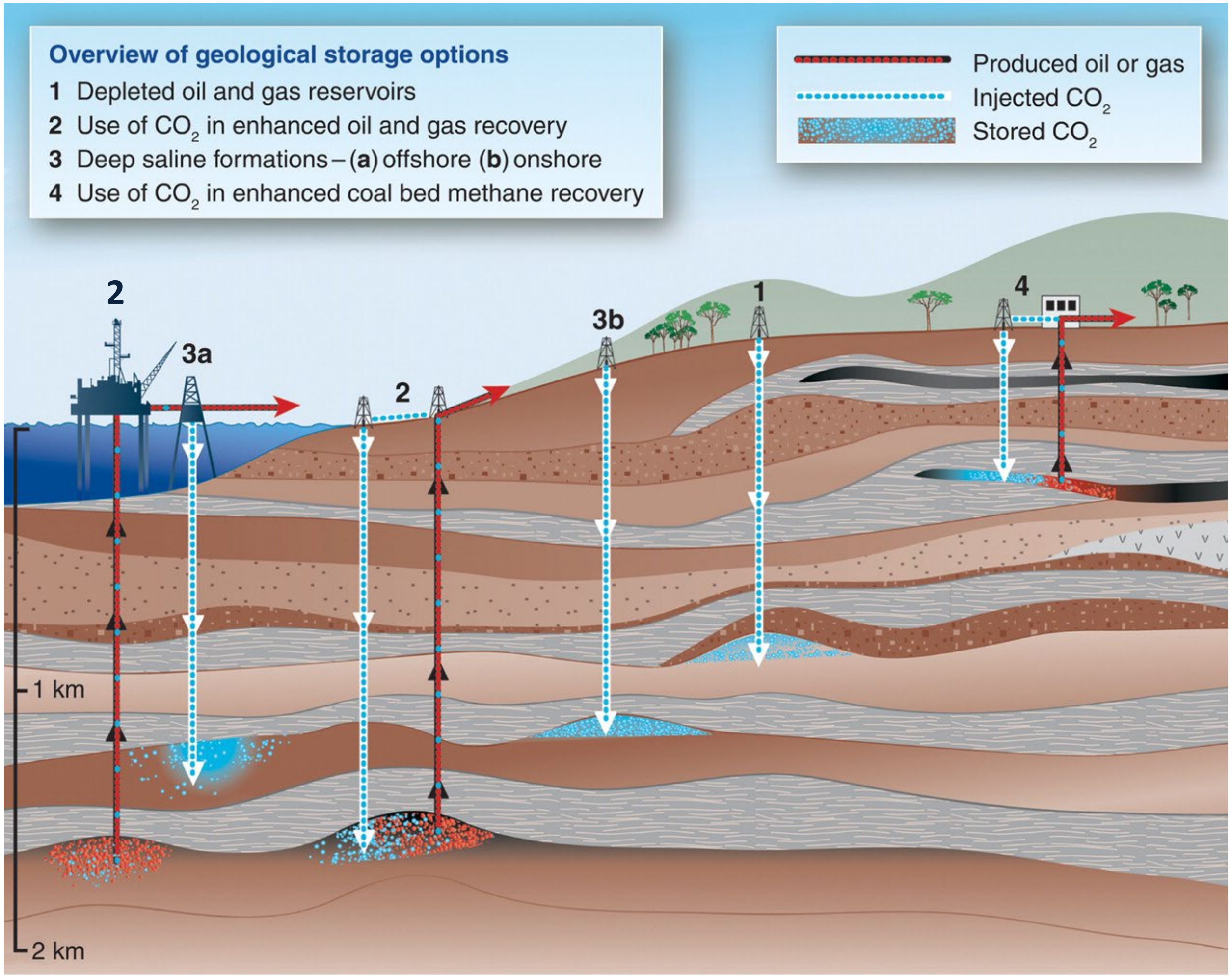
Parajuli, S. et al. *Langmuir* (2019) 35, 12061–12070.

CNC Adsorption Energy and Interfacial Tension Affects Emulsion Stability



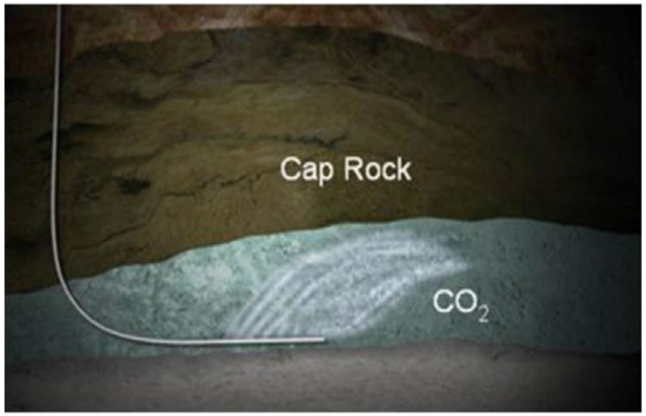
Parajuli, S. et al. *Langmuir* (2019) 35, 12061–12070.

Underground Sequestration of CO_2

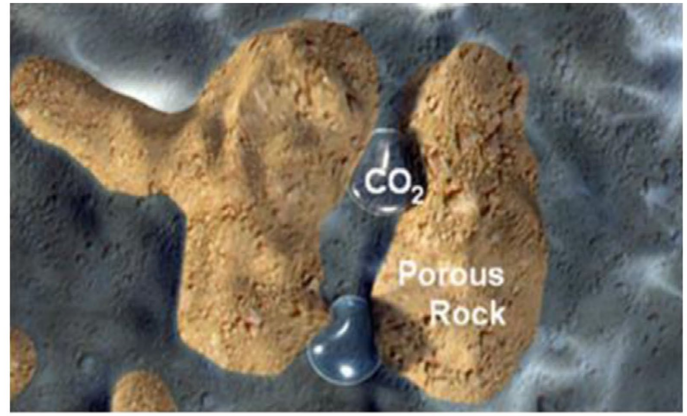


Orr, F.M. *Science* (2009) 325, 1656-1658

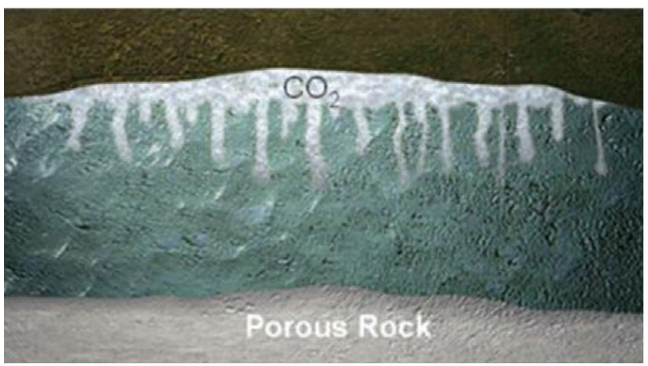
CO2 Trapping Mechanisms



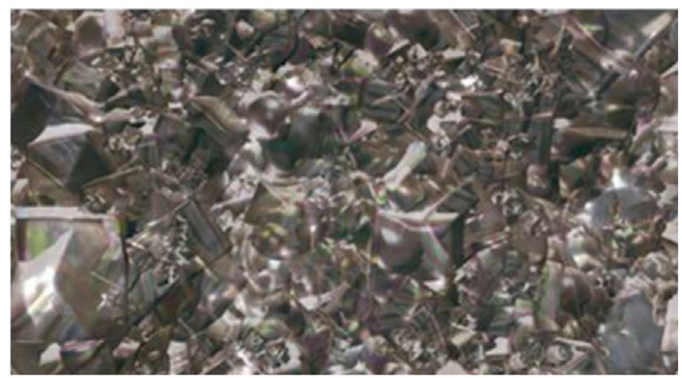
a) Structural/stratigraphic trapping



b) Residual/capillary trapping



c) Solubility trapping



d) Mineral trapping

CO_2 Leakage

ESCAPE ROUTES

- Defective well seals
- Faults
- Fractures in Caprock

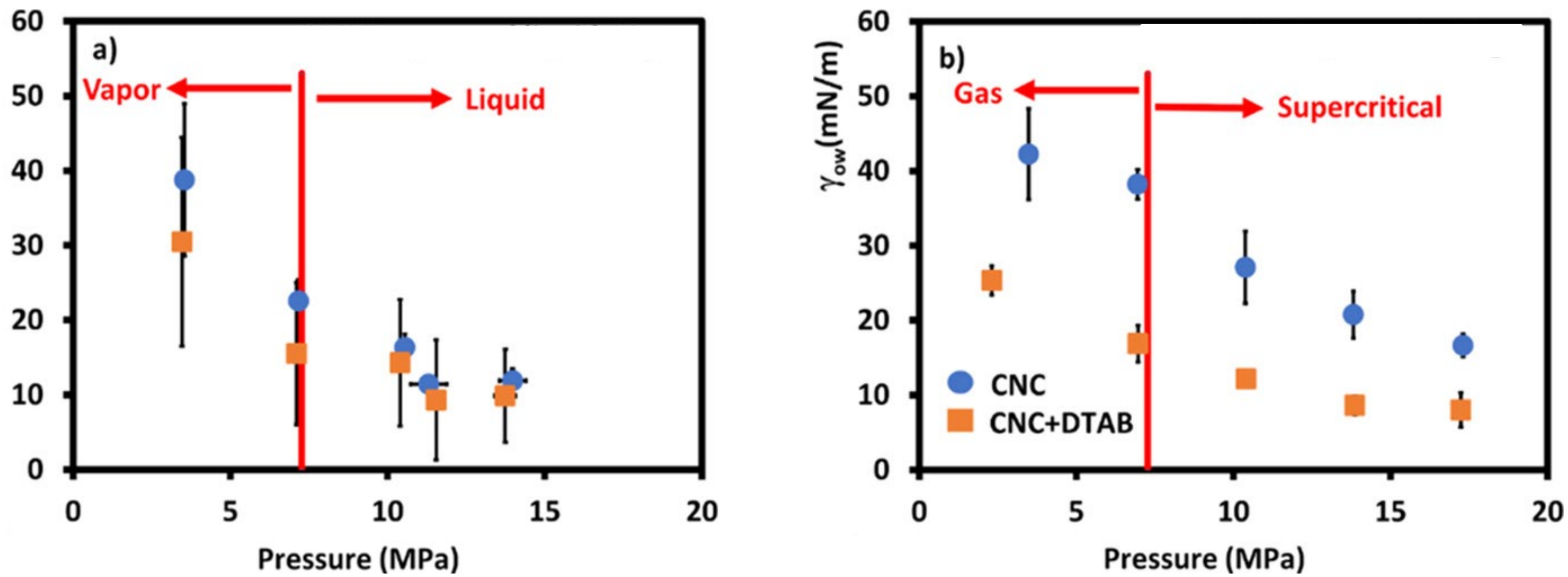
REMEDIATION METHODS

- Injection shut-off
- Hydraulic pressure management
- Addition of sealants or physical barriers
- Removal of CO_2

Interfacial Tension with DTAB

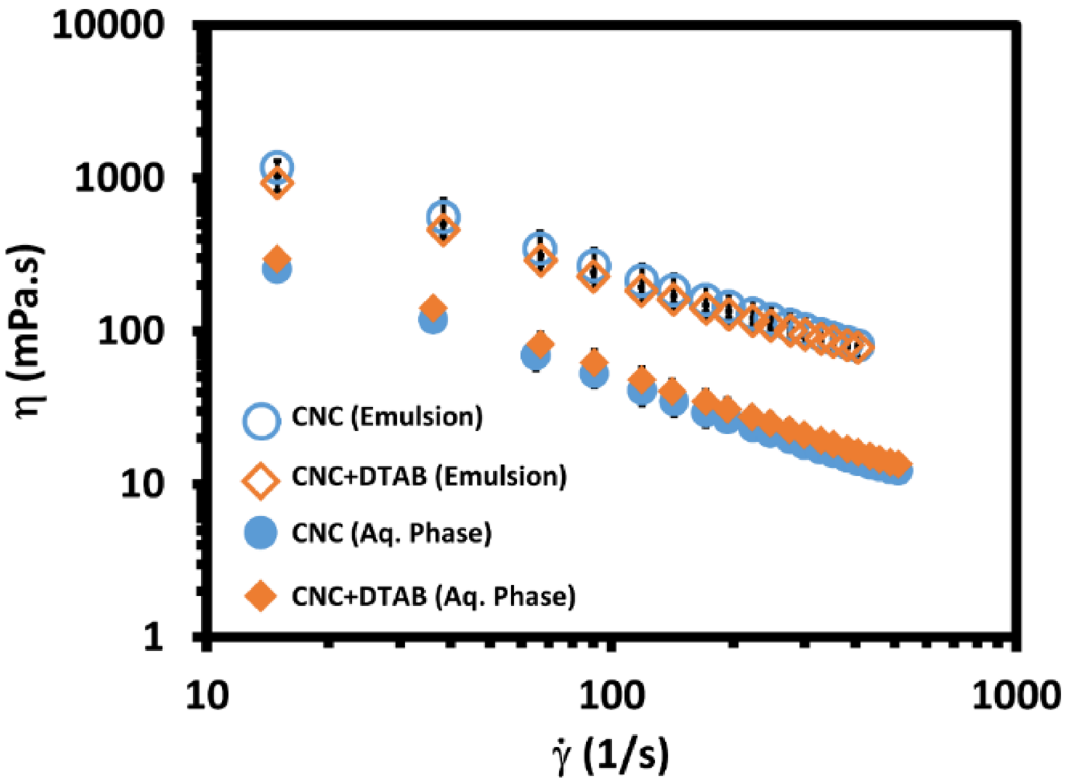
CNC at 1.5 wt%
DTAB at 0.45 g/L

25°C **70°C**



Parajuli, S., et al. *ACS Appl. Nano Mater.* (2020) 3, 12198–12208.

Heptane/Brine Emulsion Viscosity



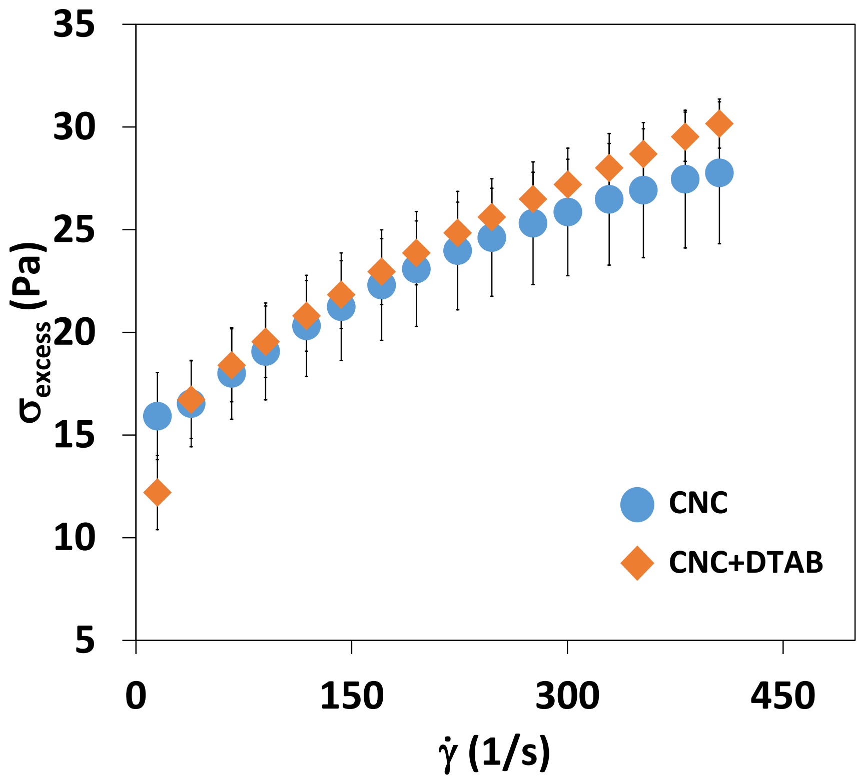
Ambient Conditions (Emulsion)

- Shear thinning
- Increased viscosity caused by interfacial excess stress

Parajuli, S., et al. *ACS Appl. Nano Mater.* (2020) 3, 12198–12208.

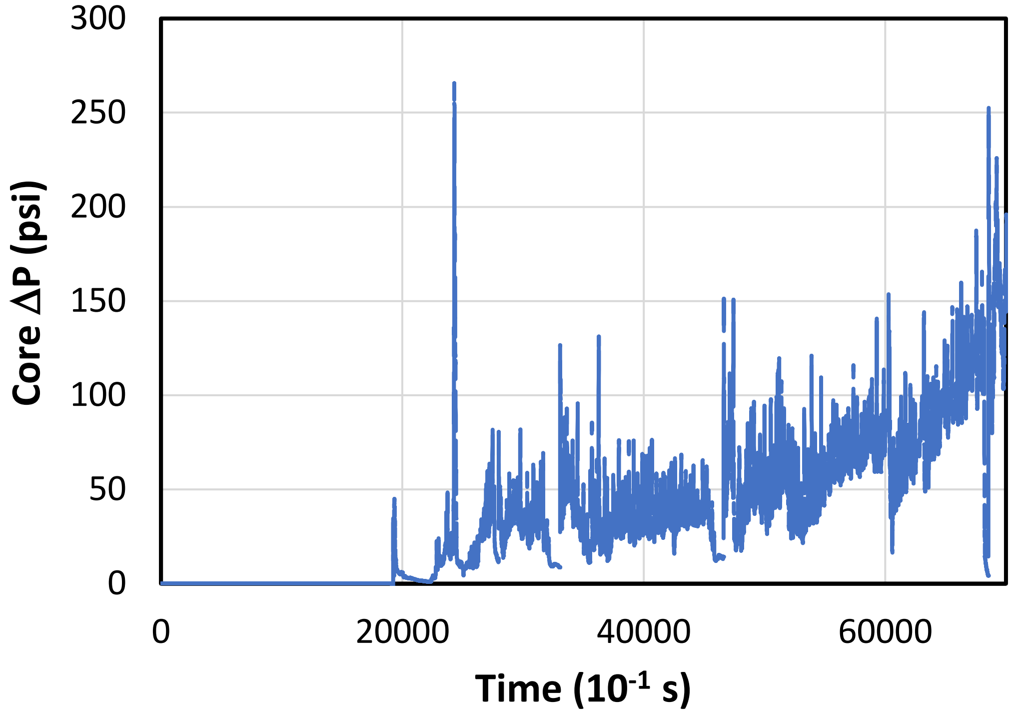
Surface Excess Stress

$$\sigma_s = \sigma - (1 - \phi_o)\sigma_{aq} - \phi_o\sigma_{aq}$$



Foam Transport: Berea Sandstone Core

- Preflooded with DTAB
- Room temperature
- 3,000 psi



CO_2 Foam Viscosity

	μ_{app} (mPa.s)	μ_{bulk} (mPa.s)
CNC only	7.90 ± 2.54	15 ± 0.57
CNC only / CO_2	1.58 ± 1.18	15.78 ± 20.24
CNC + CAA	3.71 ± 2.03	12.8 ± 2.0
CNC + CAA / CO_2	1.34 ± 0.87	18.51 ± 79.2

μ_{app}- apparent viscosity in the packed bed (Darcy's equation)
μ_{bulk}- bulk viscosity in capillary coil (Hagen Poiseuille equation)