Investigating the impact of induced calcite precipitation on the capillary pressure-saturation relation: Experimental plans

SFB 1313 Seminar 2018

Johannes Hommel: Own project, associated to C05
SFB 1313,

Project C05
SFB 1313, Project C05: What is it about?

• Investigate changes in the pore space and the associated alteration of the permeability.

• Use Magnetic Resonance Imaging (MRI) and X-ray computer microtomography (µCT) to assess changes in porous media.

• Measure porosity-permeability relations for different fluid-solid reactions:
  • salt precipitation during evaporation,
  • microbially-induced calcite precipitation,
  • dissolution during chemical stimulation.

• Who: Sander Huisman, Andreas Pohlmeier, Holger Steeb, + student
Own Project:

Existing Model Concept
Experiments
Why investigate Induced Calcite Precipitation (ICP)?

→ reduce flow (reduce $K$ and $\phi$), leakage mitigation

→ (increase mechanical strength)

Phillips et al. 2013
Engineered applications of ureolytic biomineralization: A review.
Important Reactions

Urease or ureolytic microbes are injected or thermal ureolysis occurs

Ureolysis agent: enzyme $\rightarrow$ EICP, microbes $\rightarrow$ MICP, thermal $\rightarrow$ TICP

$$\text{CO(NH}_2\text{)}_2 + 2\text{H}_2\text{O} \xrightarrow{\text{urease}} 2\text{NH}_3 + \text{H}_2\text{CO}_3$$

ureolysis

$$\text{H}_2\text{CO}_3 \xleftrightarrow{} \text{HCO}_3^- + \text{H}^+$$

dissociation of carbonic acid

$$\text{HCO}_3^- \xleftrightarrow{} \text{CO}_3^{2-} + \text{H}^+$$

dissociation of bicarbonate ion

$$2\text{NH}_4^+ \xleftrightarrow{} 2\text{NH}_3 + 2\text{H}^+$$

dissociation of ammonia

$$\text{Ca}^{2+} + \text{CO}_3^{2-} \xleftrightarrow{} \text{CaCO}_3\downarrow$$

calcite precipitation/dissolution
Model Concept: Scale

Pore scale → averaging → REV scale

- Water
- Solute
- Suspended biomass
- Calcite
- Biofilm
- CO₂
- Rock
Balance Equations

- Mass balance equation of components

\[
\sum_{\alpha} \frac{\partial}{\partial t} (\phi_{\alpha} x_{\alpha}^{\kappa} S_{\alpha}) + \nabla \cdot (\rho_{\alpha} x_{\alpha}^{\kappa} \mathbf{v}_{\alpha}) - \nabla \cdot (\rho_{\alpha} D_{\alpha,pm}^{\kappa} \nabla x_{\alpha}^{\kappa}) = q_{\kappa}
\]

- Mass balance for the immobile components / solid phases:

\[
\frac{\partial}{\partial t} (\rho_{\varphi} \phi_{\varphi}) = q_{\varphi}
\]

- Energy balance:

\[
\frac{\partial}{\partial t} \left( (1 - \phi_{0}) \rho_{s} c_{s} T \right) + \sum_{\varphi} \left[ \frac{\partial}{\partial t} (\rho_{\varphi} \phi_{\varphi} c_{\varphi} T) \right]
+ \sum_{\alpha} \left[ \frac{\partial}{\partial t} (\phi_{\alpha} u_{\alpha} S_{\alpha}) - \nabla \cdot (\rho_{\alpha} h_{\alpha} \mathbf{v}_{\alpha}) \right]
- \nabla \cdot (\lambda_{pm} \nabla T) = q_{h}
\]
Sources & Sinks: Common

Urea:
\[ q^{\text{urea}} = -r^{\text{urea}} \]

Total nitrogen:
\[ q^{\text{NH}_{\text{tot}}} = 2r^{\text{urea}} \]

Calcium:
\[ q^{\text{Ca}^{2+}} = r^{\text{diss}} - r^{\text{precip}} \]

Total carbon:
\[ q^{\text{C}_{\text{tot}}} = r^{\text{urea}} + r^{\text{diss}} - r^{\text{precip}} \]

Calcite:
\[ q^c = r^{\text{precip}} - r^{\text{diss}} \]

Precipitation rate
\[ r^{\text{precip}} = f \left( A_{\text{interface}}, \Omega = \frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{K_{sp}}, T \right) \]

Dissolution rate
\[ r^{\text{diss}} = f \left( A_{\text{interface}}, \Omega = \frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{K_{sp}}, \text{pH}, T \right) \]

Ureolysis rate (MICP)
\[ r^{\text{MICP}}_{\text{urea}} = f \left( \phi_{\text{biofilm}}, C^\text{urea}_w \right) \]

Ureolysis rate (EICP)
\[ r^{\text{EICP}}_{\text{urea}} = f \left( \phi_e, C^e_w, \text{pH}, C^\text{urea}_w, C^\text{NH}_4^+_w, T \right) \]

Ureolysis rate (TICP)
\[ r^{\text{TICP}}_{\text{urea}} = f \left( C^\text{urea}_w, T \right) \]
Model Summary

- Complex REV-scale models for
  - Two-phase flow and transport
  - Biogeochemical reactions

- MICP: 10 years of development

- EICP and TICP: under development

- No impact of ICP on two-phase flow yet!
Why is the capillary pressure-saturation relation relevant for modeling ICP?

→ reduce flow (reduce \( K \) and \( \phi \)), leakage mitigation

→ change in pore geometry
→ change in 2-phase flow properties!

→ Many relevant applications with 2p!

Phillips et al. 2013
Engineered applications of ureolytic biomineralization: A review.
Experimental plans: EICP and $p_c - S_w$
Adapting Capillary Pressure

• First step: implementing Leverett scaling of capillary pressure:

\[ J(S_w) = \text{const.}(S_w) = \frac{p_c(\phi)}{\sigma \cos \Theta} \sqrt{\frac{K(\phi)}{\phi}} = \frac{p_{c,0}}{\sigma \cos \Theta} \sqrt{\frac{K_0}{\phi_0}} \]

Assuming that \( \sigma \cos \Theta \) is constant:

\[ \rightarrow p_c(S_w, \phi) = p_c(S_w, \phi_0) \sqrt{\frac{K_0 \phi}{K(\phi) \phi_0}} \]

\(^1\)M. Leverett. “Capillary behaviour in porous solids”. In: Transactions of the AIME 142 (1941), pp. 159–172.
Adapting Capillary Pressure

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Mainly a modification of the entry pressure, as:

\[ p_c(S_w, \phi_0) = p_d \left( \frac{S_w - S_{w,r}}{1 - S_{w,r}} \right)^{-\frac{1}{\chi}} \]

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• Second step: experimental investigation:

\( p_c(S_w) \) measurements of samples mineralized to various degrees.

\(^1\)M. Leverett. “Capillary behaviour in porous solids”. In: Transactions of the AIME 142 (1941), pp. 159–172.
Adapting Capillary Pressure: Planned Experiments

Is Leverett scaling of capillary pressure sufficient?

\[ p_c(S_w, \phi) = p_c(S_w, \phi_0) \sqrt{\frac{K_0 \phi}{K(\phi)\phi_0}} = p_d,0 \sqrt{\frac{K_0 \phi}{K(\phi)\phi_0}} \left( \frac{S_w - S_{w,r}}{1 - S_{w,r}} \right)^{-\frac{1}{\lambda}} \]

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Adapting Capillary Pressure: Planned Experiments

Or is there a need for more complex $p_c(S_w, \phi)$ relations?

\[ p_c(S_w) = p_d \left( \frac{S_w - S_{w,r}}{1 - S_{w,r}} \right)^{-\frac{1}{\chi}} \rightarrow p_c(S_w, \phi) = p_d(\phi) \left( \frac{S_w - S_{w,r}(\phi)}{1 - S_{w,r}(\phi)} \right)^{-\frac{1}{\chi(\phi)}} \]
State of the lab in spring
State of the lab at the moment:
Collaborations

- Montana State University: kinetics, lab and field-scale experiments

- C04 and C05: share experimental data (porosity, permeability) obtained at different scales with different methods

  - C04: 2D exp., µm-cm scale, Microscope and µCT images, M/EICP, experiments and pore-(network)-scale modeling

  - C05: 3D exp., cm-dm scale, MRI and µCT images, MICP, salt prec/diss, experiments only

- Own project: 3D exp., mm-cm scale, µCT images, EICP (exp.), M/E/TICP (REV-scale model)

- Other projects?
Thank you!

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DuMuX  All simulations conducted with DuMuX www.dumux.org
Experiment setup sketch for mineralization

as a „by product“ also measuring porosity-permeability relation

→ Relevant for Leverett scaling
Experiment setup sketch for $p_c$-$S_w$ relations

Syringe pumps: either injecting air or extracting water

Or simultaneous injection of oil and water

$p_c$ $S_w$