Interpretation of permeability change due to effective stress with special focus on pore space geometry

Coupling of hydro-mechanical properties of porous media

Guido Blöcher, Harald Milsch & Günter Zimmermann
Two different sandstones (Flechtinger and Bentheimer) were investigated:

- Determine the effective pressure ($p_{\text{eff}}=p_{c}-p_{p}$) dependency of Skempton coefficient $B$ and the permeability $k$
- Analysing the pore space geometry
- Derive linkages between pore space geometry and transport properties
Skempton Coefficient B Measurement at the Mechanical Test System MTS

**Sample dimension:**
- length: 10cm
- diameter: 5cm

**Experiment conditions:**
- **fully undrained**
- pre-conditioned
- confining pressure range $p_c = 5$ to $60$MPa

**Measurement:**
- pore pressure $p_p$

**Result:**
- Skempton coefficient $B = \frac{dp_p}{dp_c}$
Sample dimension:
  length: 4cm
  diameter: 3cm
  cross sectional area \( A = 7.07 \text{cm}^2 \)

Experiment conditions:
  **drained**
  \( T = 40°C \)
  0.1 molar NaCl- brine
  confining pressure range \( p_c = 5 \) to 47MPa
  pore pressure range \( p_p = 2.5 \) to 42MPa
  flow rate range \( Q = 0.05 \) to 30 ml/min

Measurement:
  pore pressure gradient \( \text{grad}(p_p) \)

Result:
  permeability \( k = -\frac{Q \cdot \eta}{A \cdot \text{grad}(p_p)} \)
Results of the Laboratory Experiments

Skempton coefficient vs Permeability

- **4 - 25 MPa effective pressure**
- **3 - 29 MPa effective pressure**

Skempton coefficient

- **Saturation effects**

Permeability
Pore Space Analysis

Porosity

**Bentheimer:**
- total porosity: 19.23-26.35
- pore radii: 40-110 microns
- pore cavity to throat ratio: small

**Flechtinger:**
- total porosity: 9.54-10.73
- pore radii: 6.5-200 microns
- pore cavity to throat ratio: high

**Pore cavity-throat-ratio**
- mercury injection assumes cylindrically shaped pores ➔ determined radius is close to pore throat radius
- 2D image analysis directly determines the pore radii

➔ Gap between Mercury injection and 2D image analysis indicates the pore cavity to throat ratio
Pore Space Analysis

Pore Model

<table>
<thead>
<tr>
<th>Measured pore types</th>
<th>2D Image Analysis</th>
<th>Skempton Experiment</th>
<th>Permeability Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catenary pores</td>
<td>X</td>
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<td>X</td>
</tr>
<tr>
<td>Cul-de-sac pores</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Closed pores</td>
<td>X</td>
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Note: The ratio of Catenary, Cul-de-sac and Closed pores is changing due to effective pressure.
Analytical Examination of Permeability and Skempton Coefficient

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<td>dk/dp_{eff} [m²/MPa]</td>
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Pore Space Analysis

Circularity

\[ C = 4\pi \frac{A_p}{l^2} \]

- \( A_p \) → pore area
- \( l \) → perimeter length

\[ \frac{0.0}{0.1} \quad \frac{0.1}{0.2} \quad \frac{0.2}{0.3} \quad \frac{0.3}{0.4} \quad \frac{0.4}{0.5} \quad \frac{0.5}{0.6} \quad \frac{0.6}{0.7} \quad \frac{0.7}{0.8} \]

Circularity

- Flechtinger
- Bentheimer

Guido Blöcher

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Numerical Examination of Skempton Coefficient

Skempton coefficient varies for each single pore from 0.32 to 0.68 dependent on the pore shape.
Two mechanisms lead to a change in porosity, Skempton coefficient and permeability with changing effective stress:

1. A pore separation by closing of pore throats
   - Caternary pore $\rightarrow$ Cul-de-sac pore leads to a decrease of permeability
   - Cul-de-sac $\rightarrow$ Closed pore leads to a decrease of Skempton coefficient
   - The separation of pores depends on the pore cavity to throat ratio

2. A poro-elastic deformation of the pore space itself
   - poro-elastic deformation affects porosity, Skempton coefficient and permeability
   - The change in Skempton coefficient is highest
   - Irregularly shaped pores are more susceptible to poro-elastic deformation
Qualitative Interpretation for Flechtinger Sandstone

Observation:
- High circularity
- High pore cavity-throat-ratio
- Continuous decrease of permeability and Skempton coefficient with effective pressure increase

Interpretation:
- No change of the pore shape
- Separation of pores
- Cut-off of flow path leads to a change in permeability and Skempton coefficient
Qualitative Interpretation for Bentheimer Sandstone

**Observation:**
- Low circularity (irregular pore shapes)
- Low pore cavity-throat-ratio
- High decrease in Skempton coefficient at low effective pressure and no significant change in permeability

**Interpretation:**
- Sensitive for poro-elastic deformation
- No separation of pores
- High poro-elastic deformation at low effective pressure. After stiffening of the frame work no further change in B and k.
Conclusion

• Two types of sandstone (Flechtinger and Bentheimer) were investigated.
• Both samples show differences in effective pressure dependencies as expressed by their Skempton coefficient and permeability.
• By means of a three pore type model in combination with a heterogeneous pore space geometry change a qualitative interpretation is possible.

Future Work

• A quantification of the geometry change will be necessary.
• A direct method to measure the geometry change due to effective pressure change must be developed.
• Further experiments to validate the results of this work.