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Hydraulic and Sleeve Fracturing Laboratory Experiments on 6 Rock Types

Sebastian Brenne, Michael Molenda, Ferdinand Stöckhert and Michael Alber

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http://dx.doi.org/10.5772/56301

1. Introduction

Hydraulic tensile strength is a crucial value for planning reservoir stimulation and stress measurements. It is used in the classical breakdown pressure \( P_b \) relation by Hubbert & Willis [1], where \( P_b \) is a function of major and minor principal horizontal stresses \( S_H \) and \( S_h \), hydraulic tensile strength \( \sigma_T \) and pore pressure \( P_0 \):

\[
P_b = 3S_h - S_H + \sigma_T - P_0
\]  

(1)

For hydraulic fracturing laboratory experiments (MiniFrac – MF) under isostatic confining pressure \( P_m \) this might be reduced to:

\[
P_b = cP_m + \sigma_T - P_0
\]  

(2)

The coefficient \( c \) should be equal to two when porepressure is neglected. However, many laboratory experiments [2,3] resulted in values of about 1 for \( c \), which might be explained by poroelastic effects.

Thus, when poroelasticity is excluded in the experiments by taking dry samples and sealing off the central borehole by an impermeable membrane (like a polymer tube), one would expect that \( c \) equals two and \( \sigma_T \) will be in the range of the tensile strength as determined by other tensile strength tests.
However, experiments with jacketed boreholes (sleeve MiniFrac – SMF) yield remarkable high values for $c$ (about 6 to 8) and also for $\sigma_T$ (about 3 to 5 times the tensile strength of the material) [4]. As a consequence we use a linear elastic fracture mechanics approach to evaluate our experiments.

### 1.1. Theory of hydraulic and sleeve fracturing on hollow cylinders

Fracture mechanics deal with stress concentrations around fractures and the definition of propagation criteria for fractures. The theory is essentially based on the works of Griffith [5] and Irwin [6], which led to the introduction of the stress intensity factor $K$.

$$K = \sigma \sqrt{\pi a}$$  \hfill (3)

$K$ represents the magnitude of the elastic stress singularity at the tip of a fracture of the length $2a$ subjected to a uniform stress $\sigma$. With this concept, it is possible to formulate a simple fracture propagation criterion $K = K_C$. The fracture propagates when $K$ reaches a critical value $K_C$ (fracture toughness) with the fracture toughness assumed to be a property of the rock.

Mode I stress intensity factors ($K_I$) for arbitrary tractions ($\sigma(x)$) applied to the surface of a fracture of the length $2a$ may be computed by following formula [7,8]:

$$K_I = \frac{1}{\pi \sqrt{a}} \int_{-a}^{a} \sigma(x) \left( \frac{a + x}{a - x} \right)^{1/2} dx$$  \hfill (4)

The direction of propagation is the x-axis and the stresses are applied perpendicular to the fracture. As can be seen from equation (4), $K_I$ increases with growing fracture length. A simple, 2-dimensional model was assumed for determination of stress intensity factors at the crack tips of the hydraulically induced fractures in MF and SMF tests.

Two fractures of length $a$ are radially emanating from a circular hole of radius $r$ in an infinite plate subjected to a compressive far field stress of the magnitude $P_m$. A fluid pressure $P_{inj}$ is acting on the borehole wall and the pressure inside the fractures is either zero (SMF) or equal to the pressure in the borehole (MF: $P_{frac} = P_{inj}$). Stress intensities on the fracture tips can be determined by superposition of stress intensity factors resulting from each loading type [2,3]:

$$K_{I-MF} = K_I(P_m) + K_I(P_{inj}) + K_I(P_{frac})$$  \hfill (5)

$$K_{I-SMF} = K_I(P_m) + K_I(P_{inj})$$  \hfill (6)
$K_{I-MF/SMF}$ are not only dependent on the fracture length $a$ (cf. Equations (3) and (4)) but also on the borehole radius $r$ (see Appendix).

$K_{I-MF}$ (full pressure in the fracture) gives an upper bound for stress intensities in this geometry (actual $K_{I-MF}$ might be lower due to a negative pressure gradient inside the fracture), while $K_{I-SMF}$ is only induced by the pressure in the borehole and far-field stresses and is therefore substantially lower than $K_{I-SMF}$ (Figure 1).

![Figure 1](image)

**Figure 1.** Left side: superposition of stress intensities by each loading type. Right side: stress intensity factor versus fracture length from analytical (infinite plate) and numerical (hollow cylinder) calculations for $r=3$ mm, $P_{inj}=50$ MPa, $P_m=0$ and an outer radius $R$ of the hollow cylinder = 30 mm.

As an analytical solution for $K_{I}(P_m)$ and $K_{I}(P_{inj})$ for the ring geometry (corresponding to the hollow cylinder) is quite complex, we used the simpler solutions for a circular hole in an infinite plate as described by Rummel and Winter [2,3] (cf. Appendix). We compared the results of numerical simulations for the ring geometry with analytical solutions for the infinite plate. These results indicate that the simplification might be valid for fracture lengths smaller than $a \approx R - r$ with $R = 10r$ ($R$ is the outer radius of the ring geometry (cf. Figure 1).

Solving $K_{I-MF}$ and $K_{I-SMF}$ for $P_{inj}$ and setting $K_{I-MF} = K_{I-SMF} = K_{IC}$ (mode I fracture toughness) yields a critical injection pressure ($P_C(a)$) for each crack length $a$. If $P_{inj}$ reaches $P_C(a)$, the fracture will propagate. From Figure 2 it can be seen, that $P_C(a)$ is very large for very small crack lengths. In consequence, the presence of microcracks is required for the formation of macroscopic fractures.
Figure 2. Critical injection pressure for fracture propagation $P_c$ depending on fracture length $a$ for $P_m = 0$. Borehole radii $r = 3$ mm (left), $r = 2$ mm (right).

MF-equation (Equation 13) with full injection pressure in the fracture yields unstable fracture propagation at constant injection pressures as soon as microcracks start to propagate. On the other hand, the SMF-equations (Equation 14) show a minimum. Thus, after a fracture reaches the crack length corresponding to the minimum critical injection pressure, stable fracture propagation (i.e. to propagate the fracture, the injection pressure has to be increased) could be expected.

To calculate the coefficient $c$ from Equation 2, we assume the presence of microcracks of a fixed length $a_0$ in the sample. The corresponding $P_c(a_0)$ versus $P_m$ for the MF case (pressure in fracture = injection pressure) yields a coefficient $c = 1$, which is independent of $a_0$. $P_c(a_0)$ while for SMF the $c$ value depends strongly on the assumed microcrack length $a_0$ and gives $c > 2$ (increasing $a_0$ yield higher $c$).

2. Sample preparation and rock testing

The core specimens are drilled either with 40 mm or 62 mm water cooled diamond core drills. Core end planes are cut with a water flushed diamond saw blade and ground coplanar to a maximum deviation of ± 0.02 mm. The length and diameter ratio is chosen between 1.5:1 and 2.25:1. After sample preparation core specimens were dried for two days at a temperature of 105°C. For calculations of porosity $\Phi$, measurements of bulk density $\rho_d$ and of grain density $\rho_g$ via pycnometer were done. Static geomechanical parameters
were determined by uniaxial and triaxial compressive as well as Brazilian disc tensile strength test series according to ISRM and DGGT suggested methods [9,10]. Mode I fracture toughness was determined using the Chevron notched three-point bending test according to [9]. Furthermore, a dynamic rock parameter, the compressional ultra-sonic wave velocity ($v_p$) was measured. For MF/SMF specimens a central axial borehole was drilled into cores, using a water flushed diamond hollow drill with an outer diameter of 4 mm or 6 mm.

<table>
<thead>
<tr>
<th>rock type</th>
<th>era &amp; period</th>
<th>quarry localization</th>
<th>Microstructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>marble</td>
<td>Triassic</td>
<td>Carrara, Italy</td>
<td>coarse monocrystalline polygonal fabric</td>
</tr>
<tr>
<td>limestone</td>
<td>Jurassic upper Malm</td>
<td>Treuchtlingen, South Germany</td>
<td>micritic limestone with abundant fossils and stylolites</td>
</tr>
<tr>
<td>sandstone</td>
<td>Carboniferous Mississippian</td>
<td>Dortmund/Hagen, West Germany</td>
<td>fine-grained arcose</td>
</tr>
<tr>
<td>andesite D</td>
<td>Permian Rotliegend</td>
<td>Doenstedt, N German Basin</td>
<td>porphyric fine-grained partly altered and pre-fractured</td>
</tr>
<tr>
<td>rhyolite</td>
<td>Permian Rotliegend</td>
<td>Flechtingen, N German Basin</td>
<td>porphyric fine-grained partly pre-fractured and sealed joints</td>
</tr>
<tr>
<td>andesite R</td>
<td>Permian Rotliegend</td>
<td>Thuringian Forest Rotkopf</td>
<td>porphyric coarse-grained and pre-fractured</td>
</tr>
</tbody>
</table>

Table 1. Rock types used in our experiments.

2.1. Stress field and injection

Figure 3 shows schematically the components of the MF and SMF experimental set-up. The stress field is induced by a hydraulic ram (capacity 4500 kN) through a servo controlled MTS Test Star II system with a Hoek triaxial cell which is pressurized using a hand pump to achieve simultaneous pressure increase of confining pressure and axial load. In all tests axial stress is set to be 2.5 MPa higher than $P_m$ to prevent leakage. Distilled water is pumped into borehole as the injection fluid (MF) or into a polymer tube inside the borehole (SMF). A servo controlled pressure intensifier with a maximum injection pressure of 105 MPa was used to perform a constant pumping rate of 0.1 ml/s. With this apparatus also steady-state flow tests were conducted to obtain rock permeability values (according to the procedure described in [11]).
2.2. Acoustic emission monitoring

Acoustic Emission (AE) signals are acquired with an AMSY5 Acoustic Emission Measurement System (Vallen Systeme GmbH, Germany) equipped with 5 Sensors of type VS150-M. The VS150-M Sensors operate over a frequency range of 100-450 kHz with a resonance frequency at 150 kHz. Due to machine noise in the range below 100 kHz incoming signals are filtered by a digital bandpass-filter that passes a frequency range of 95-850 kHz. AE data are sampled with a sampling rate of 10 MHz. The sensors are fixed using hot-melt adhesive to ensure best coupling characteristics. Pencil-break tests (Hsu-Nielsen source [12]) and sensor pulsing runs (active acoustic emission by one sensor) are used to test the actual sensor coupling on the sample.

3. Results

3.1. Petrophysical and mechanical parameters

An overview of the rock properties is given in Table 2. A wide range of low porosity/permeability rocks with $K_{IC}$ from 1 to 2 MPa $\cdot \sqrt{m}$ were tested.
Table 2. Mean values and standard deviations of petrophysical and mechanical parameters of tested rocks: dry bulk density $\rho_d$, porosity $\Phi$, permeability $k$, compressive wave velocity $v_p$, fracture toughness from Chevron notched three-point bending tests $K_{IC}$, cohesion $C$ and friction angle $\phi$ from a Mohr-Coulomb fit, Young’s modulus $E_{stat}$, $\sigma_T$ as determined by Brazilian disc tensile strength tests.

<table>
<thead>
<tr>
<th>rock type</th>
<th>$\rho_d$ [g/cm$^3$]</th>
<th>$\Phi$ [-]</th>
<th>$k$ [m$^2$]</th>
<th>$v_p$ [m/s]</th>
<th>$K_{IC}$ [MPa - $\sqrt{m}$]</th>
<th>$C/\phi$ [MPa]/[°]</th>
<th>$E_{stat}$ [GPa]</th>
<th>$\sigma_T$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>marble</td>
<td>2.71 ± 0.002</td>
<td>0.40 ± 0.08</td>
<td>1E-19</td>
<td>5.67 ± 0.06</td>
<td>1.57 ± 0.11 (N=3)</td>
<td>29/22</td>
<td>36.0 ± 6.4</td>
<td>6.4 ± 1.5</td>
</tr>
<tr>
<td>limestone</td>
<td>2.56 ± 0.008</td>
<td>5.64 ± 0.04</td>
<td>1E-18</td>
<td>5.59 ± 0.05</td>
<td>1.19 ± 0.14 (N=8)</td>
<td>27/53</td>
<td>32.2 ± 2.2</td>
<td>8.2 ± 2.2</td>
</tr>
<tr>
<td>sandstone</td>
<td>2.57 ± 0.006</td>
<td>4.39 ± 0.06</td>
<td>8E-18</td>
<td>4.61 ± 0.13</td>
<td>1.54 ± 0.13 (N=4)</td>
<td>36/50</td>
<td>29.4 ± 13.2</td>
<td>1.6 ± 2.1</td>
</tr>
<tr>
<td>rhyolite</td>
<td>2.63 ± 0.015</td>
<td>1.02 ± 0.12</td>
<td>9E-19</td>
<td>5.39 ± 0.34</td>
<td>2.16 ± 0.10 (N=4)</td>
<td>20…36/55</td>
<td>30.2 ± 15.8</td>
<td>15.8 ± 3.2</td>
</tr>
<tr>
<td>andesite D</td>
<td>2.72 ± 0.023</td>
<td>0.51 ± 0.09</td>
<td>6E-19</td>
<td>5.26 ± 0.28</td>
<td>1.90 ± 0.08 (N=2)</td>
<td>20…41/50</td>
<td>28.7 ± 14.6</td>
<td>4.5 ± 2.1</td>
</tr>
<tr>
<td>andesite R</td>
<td>2.60 ± 0.013</td>
<td>1.70 ± 0.08</td>
<td>4E-20</td>
<td>4.35 ± 0.27</td>
<td>1.63 ± 0.24 (N=4)</td>
<td>31/46</td>
<td>21.3 ± 11.4</td>
<td>11.4 ± 2.8</td>
</tr>
</tbody>
</table>

3.2. MF and SMF experiments

A schematic example of typical experiment data for MF and SMF tests is shown in Figure 4. Acoustic emission recordings are used to identify fracture processes in the test specimens. AE counts (threshold crossings per time interval – corresponding to AE activity) can directly be linked to localized fracture propagation [4]. The pressure at which the AE count rate raises rapidly is defined as $P_{AE}$, which is further used as initial fracture propagation pressure. $P_{AE}$ is picked where the AE count rate permanently exceeds 1/10 of the test’s average (see Figure 4).

In MF experiments, there is almost no AE activity prior to failure. Failure occurs in a very short time span just before sample breakdown (which occurs at maximum injection pressure $P_{inj\ max} = P_b$), therefore in MF experiments $P_{AE} = P_b$. In contrast, SMF experiments show an exponential increase in AE activity at injection pressures that are substantially lower than the actual breakdown pressure ($P_{AE} < P_b$), but much higher than $P_{AE}$ in MF experiments. Therefore, it is possible to interrupt the experiment after AE activity started but before sample breakdown. The latter occurs in SMF experiments when the sample is completely split into two parts, which results in a tube breakdown and therefore in an injection pressure drop. Thin sections of specimens, where the experiment was interrupted, show macroscopic fractures emanating several millimeters into the sample but without any connection to the outer surface.

Noteworthy is the discrepancy between the MF and SMF initial fracture propagation pressures $P_{AE}$ at zero confining pressure. This result would imply different hydraulic tensile strength values for the same rock type when using equation (2). Furthermore there is a significant difference between the values of coefficient $c$ calculated for MF and SMF experiments. This
can be seen clearly in Figure 5. Scale effects in $P_{AE}$ (Figure 2) with borehole radius are not evident for the 2 and 3 mm borehole radius samples due to data scattering. One single SMF test of a sandstone with a 6.35 mm borehole radius showed a significantly lower $P_{AE}$ as can be seen in Figure 5.

![Table 3](image)

Table 3. Results of all MF and SMF rock type test series in form of $P_{AE0}$ and coefficient $c$ (see equation (2)). $N$ gives the number of tested samples per lithology and borehole diameter.
Figure 5. Experimental results of MF (left) and SMF (right) initial fracture propagation pressures for different confining pressures. Dashed line – linear regression of test data. Symbol size refers to borehole radius \( r \) (small – \( r = 2 \text{mm} \); intermediate – \( r = 3 \text{mm} \); large – \( r = 6.35 \text{mm} \)).

4. Conclusion

With SMF tests, stable fracture propagation was achieved over a wide range of injection pressure. Fracture initiation can be confidently linked to the AE count rates. This can be concluded from experiments that were interrupted after \( P_{AE} \) but below breakdown pressure. Physical examination revealed the presence of distinct fractures in these specimens (see Figure 6).

Figure 6. Thin-section of a marble specimen (\( r = 2 \text{mm} \)) after SMF test. Clearly visible is a “dry” fracture (indicated by arrows) emanating radially from the borehole (at the right side of the picture). The experiment was interrupted before specimen breakdown. The fracture did apparently not propagate to the outer wall of the specimen.
Due to high data scatter, the theoretical scale effect (critical injection pressure $P_c$ is higher for smaller borehole radii) cannot be resolved by our data. However, tests with a larger ($r = 6.35$ mm) borehole give some support to the notion.

The simple fracture mechanics model is able to explain the higher $P_{AE}$ in SMF experiments. Equations 5 and 6 include the influence of fractures (with or without pressure inside), which is omitted in the classical approach (Equation 1). The high coefficient $c$ in SMF test can only be explained by assuming high microcrack lengths ($a_0 \approx 6$ mm).

We excluded poroelastic effects in our analysis due to the use of initially dry rocks with low permeabilities.

**Appendix**

Superposition of stress intensity factors for two radial cracks of length $a$ emanating from an internally pressurized ($P_{inj}$ - injection pressure in the borehole, $P_{frac}$ - pressure inside the fracture) circular hole of radius $r$ in an infinite plate subjected to an isostatic far-field stress $P_m$ as described by [2] and [3]:

\[
K_i(P_m) = P_m \sqrt{r} f_{P_m}(a,r) 
\]

\[
K_i(P_{inj}) = P_{inj} \sqrt{r} f_{P_{inj}}(a,r) 
\]

\[
K_i(P_{frac}) = P_{frac} \sqrt{r} f_{P_{frac}}(a,r)
\]

\[
f_{P_m}(a,r) = 2 \left(1 + \frac{a}{r}\right)^2 \left(1 + \frac{a}{r}\right)^{-1} \left(1 + \frac{a}{r}\right)^{\frac{1}{2}} \left(1 + \frac{a}{r}\right)^{\frac{1}{3}} \left(1 - \frac{2}{\pi} \sin^{-1} \left(\frac{1}{1 + \frac{a}{r}}\right)\right) 
\]

\[
f_{P_{inj}}(a,r) = 1.3 \frac{a}{r} + 7.8 \sin \left(\frac{2a}{r}\right) 
\]

\[
f_{P_{frac}}(a,r) = \frac{a}{r} + 1 \left(1 + \frac{a}{r}\right)^{\frac{3}{2}} \left(1 + \frac{a}{r}\right)^{-1} - 1.7 
\]
\[ f_{p_{\text{pe}}}(a,r) = \left( \pi \left( 1 + \frac{a}{r} \right) \right)^2 \left( 1 - \frac{2}{\pi} \sin^{-1} \left( \frac{1}{1 + \frac{a}{r}} \right) \right) \] (12)

Note: In equations 10 and 12 the borehole was excluded from the integration of stresses (cf. equation 4). The critical fracture propagation pressure at a given fracture length \( a \), borehole radius \( r \) and mode I fracture toughness \( K_{IC} \) for the unjacketed \( (P_{c-MF}) \) and the jacketed \( (P_{c-SMF}) \) case:

\[ P_{c-MF} = \frac{1}{f_{p_{\text{pe}}}} \left( \frac{K_{IC}}{\sqrt{r}} + P_{inj} f_{p_{\text{pe}}} \right) \] (13)

\[ P_{c-SMF} = \frac{1}{f_{p_{\text{pe}}}} \left( \frac{K_{IC}}{\sqrt{r}} + P_{inj} f_{p_{\text{pe}}} \right) \] (14)

Acknowledgements

The authors wish to thank the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety for financing our project (FKZ 0325279B). Many core specimens were prepared and analyzed by our student staff: T. Hoferichter, J. Braun, S. Hönig, K. Bartmann and A. Kraft. A great praise to the precision mechanics workshop guys for the construction of the fine working pressure intensifier system. We appreciate fruitful discussions with geomecon GmbH, Potsdam.

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