FRACTURE TOUGHNESS and TENSILE STRENGTH of
GHAWAR-KHUFF ROCK FORMATION

By
Dr. Naser A. Al-Shayea
OUTLINE

• Introduction
• Objectives
• Experimental Program
• Results & Discussions
• Conclusions
Fracture Toughness

- Rocks contain cracks, joints & fissures etc..
- Resistance against crack initiation and propagation.
Crack Propagation Modes

Mode-I

Mode-II

Mode-III
Hydrofracturing

• Used to enhance oil and gas recovery from the reservoir.

• Depends on
  – Characteristics of rock formation.
  – Depth and inclination of borehole.

• To model hydraulic fracturing, fracture toughness value is required.

• Fracture toughness value should be representative of in-situ conditions (Temperature & Pressure).
OBJECTIVES

• To determine tensile strength for outcrop and reservoir specimens.
• To determine fracture toughness for outcrop and reservoir specimens.
• To investigate how closely outcrop specimens can predict the fracture behavior under reservoir conditions.
Specimen Type

- **Advantages**
  - Core based specimens
  - Do not require machining
  - Saving of material and resources
  - Versatile specimen
Mixed Mode I-II Loading

\[ K_I = \left[ \frac{P a^{1/2}}{\pi^{1/2} RB} \right] N_I \]

\[ K_{II} = \left[ \frac{P a^{1/2}}{\pi^{1/2} RB} \right] N_{II} \]
Figure: Normalized Mixed Mode Fracture Toughness Coefficients for Brazilian Disk.
EXPERIMENTAL PROGRAM
Sample Preparation
Experimental Setup for Ambient Conditions
Experimental Setup - Res. Press. Condition
Experimental Setup - Res. Temp. Condition
RESULTS
AMBIENT CONDITIONS
Effect of Specimen Origin on $K_I$ & $K_{II}$

- $K_I$ (Outcrop)
- $K_{II}$ (Outcrop)
- $K_I$ (Reservoir)
- $K_{II}$ (Reservoir)

$a/R = 0.3$

$D = 99 \pm 1$ mm
RESERVOIR CONDITIONS
Outcrop specimens

\[ K_I = 0.043 \times \text{Con. Pressure} + K_{IC(0)} \]

\[ R^2 = 0.99 \]
$K_I$ Under Confining Pressure

- Reservoir Specimens
- Outcrop Specimens

Lithology C

Mode-I Fracture Toughness, $K_I$ (Mpa m$^{1/2}$)

Confining Pressure (Mpa)
Effect of Temperature on $K_I$
Ambient vs. Confined (outcrop)

Outcrop Specimens

- $K_I$ ($\sigma_3 = 0$ psi)
- $K_{II}$ ($\sigma_3 = 0$ psi)
- $K_I$ ($\sigma_3 = 4000$ psi)
- $K_{II}$ ($\sigma_3 = 4000$ psi)

$K_I, K_{II}$ (Mpa m$^{1/2}$)

$\beta$ (deg)

$a/R = 0.3$

$D = 98$ mm
Ambient vs. Confined (reservoir)

Reservoir Specimens
- $K_I (\sigma_3 = 0 \text{ psi})$
- $K_{II} (\sigma_3 = 0 \text{ psi})$
- $K_I (\sigma_3 = 4000 \text{ psi})$
- $K_{II} (\sigma_3 = 4000 \text{ psi})$

$a/R = 0.3$
$D = 100 \text{ mm}$
Outcrop vs. Reservoir (confined)

KI (Outcrop)
KII (Outcrop)
KI (Reservoir)
KII (Reservoir)

\[ \frac{a}{R} = 0.3 \]

\[ D = 99 \pm 1 \text{ mm} \]

\[ \sigma_3 = 4000 \text{ psi} \]
Temperature Effects on $K_I$ & $K_{II}$

Outcrop Specimens
- $K_I$(Ambient)
- $K_{II}$(Ambient)
- $K_I$(T = 116 C)
- $K_{II}$(T = 116 C)

$K_I$, $K_{II}$ (Mpa m$^{1/2}$)

$\beta$ (deg)

$a/R = 0.3$

$D = 98$ mm
### Summary of Results

<table>
<thead>
<tr>
<th>Samples</th>
<th>D (mm)</th>
<th>$K_{IC}$ Mpa (m)$^{1/2}$</th>
<th>$K_{IIIC}$ Mpa (m)$^{1/2}$</th>
<th>$K_{IIIC}/K_{IC}$</th>
<th>Test condition</th>
<th>% Increase $K_{IC}$</th>
<th>% Increase $K_{IIIC}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outcrop</td>
<td>98</td>
<td>0.43</td>
<td>0.92</td>
<td>2.140</td>
<td>Ambient*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outcrop</td>
<td>98</td>
<td>0.529</td>
<td>1.07</td>
<td>2.023</td>
<td>Temperature*</td>
<td>23</td>
<td>16</td>
</tr>
<tr>
<td>Outcrop</td>
<td>98</td>
<td>1.58</td>
<td>2.18</td>
<td>1.380</td>
<td>Confined*</td>
<td>267</td>
<td>137</td>
</tr>
<tr>
<td>Outcrop</td>
<td>84</td>
<td>0.35</td>
<td>0.65</td>
<td>1.857</td>
<td>Ambient**</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outcrop</td>
<td>84</td>
<td>0.37</td>
<td>0.68</td>
<td>1.838</td>
<td>Ambient*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outcrop</td>
<td>84</td>
<td>1.2</td>
<td>1.49</td>
<td>1.242</td>
<td>Confined**</td>
<td>243</td>
<td>129</td>
</tr>
<tr>
<td>Reservoir</td>
<td>100</td>
<td>0.408</td>
<td>0.513</td>
<td>1.257</td>
<td>Ambient*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reservoir</td>
<td>100</td>
<td>1.32</td>
<td>2.18</td>
<td>1.652</td>
<td>Confined*</td>
<td>224</td>
<td>325</td>
</tr>
<tr>
<td>Reservoir</td>
<td>100</td>
<td>0.61</td>
<td>0.56</td>
<td>0.918</td>
<td>Temperature*</td>
<td>50</td>
<td>9</td>
</tr>
</tbody>
</table>

* $a/R = 0.3$

** $a/R = 0.4$
Fracture Toughness Envelope

Brazilian Disk Tests
- Chevron Notch (outcrop)
- Straight Notch Outcrop
- Straight Notch (Reservoir)
- Outcrop (98 mm) (Confined)
- Outcrop (84 mm) (Confined)
- Outcrop (116°C)
- Reservoir (Confined)
- Outcrop (D=84 mm, a/r =0.3)
- Outcrop (D= 84 mm, a/r = 0.4 mm)

\[ S_{\text{min}}(\nu = 0.3) \]
CONCLUSIONS

• Confining pressure has significant effect on fracture toughness value; whereas effect of temperature is marginal.

• Mixed mode I-II fracture toughness results for outcrop and reservoir specimens under confining pressure are very close despite the fact that the behavior is not comparable at ambient conditions.
• The crack propagation in these rocks is best predicted by maximum stress criterion.
• Crack mostly initiated at the tip.
• Crack initiation and propagation is independent of both specimen origin and testing condition.
THANK YOU