Fracture Toughness vs. Tensile Strength for Reservoir Rocks From Saudi Arabia

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- Geology
- Rock description
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- Conclusions
Definitions

- Fracture toughness
- Tensile strength
- Reservoir rocks
- Hydraulic fracturing
Geology

- Rock samples belong to “Khuff” formation, Saudi Arabia.
- **Khuff** formation relates to early Triassic to late Permian age (215 to 270 M.Y.B.P.).
- Structural geology: outcrops in the Central Province up to 100s m altitude, and dips towards the east to a depth of 2000-4000 m in the Eastern Province.
- Thickness of the **Khuff** formation in the *Ghawar* is around 500m.
- Lithology: limestone, claystone, dolomite, anhydrite & sandstone.
- The anhydrite and carbonate sequence is subdivided into four alternating intervals. From top to bottom, the anhydrite-carbonate pairs are called Khuff A, B, C, and D.
- Lithology A as asphanitic-calcarenitic limestone, Lithology B as asphanitic limestone, Lithology C as dolomite and limestone, and Lithology D as dolomite and shale.
Map of Saudi Arabia
Schematic Section Showing Cretaceous Surface-subsurface Relationships

Geologic Time Scale

<table>
<thead>
<tr>
<th>Formation</th>
<th>Period (System)</th>
<th>Time (M.Y.B.P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quaternary</td>
<td>Tertiary</td>
<td>2, 245</td>
</tr>
<tr>
<td>Jurassic</td>
<td>Cretaceous</td>
<td>140, 283</td>
</tr>
<tr>
<td>Triassic</td>
<td>Permian</td>
<td>204, 440</td>
</tr>
<tr>
<td>Ordovician</td>
<td>Cambrian</td>
<td>245, 505</td>
</tr>
<tr>
<td>Saq</td>
<td>Pre Cambrian</td>
<td>590</td>
</tr>
</tbody>
</table>

Legend:
- Basement
- Pre Cambrian
- Cambrian
- Ordovician
- Triassic
- Permian
- Jurassic
- Cretaceous
- Tertiary
- Quaternary
- Wasa
- Buwaib
- Sulawiy
- Jilh
- Anah
- Marrat
- Jilh
- Sudair
- Khuff
- Unayzah
- Qasim
- Marrat
- Aruma
## Stratigraphic Column of the Khuff Formation in the Ghawar Field

<table>
<thead>
<tr>
<th>AGE</th>
<th>FORMATION</th>
<th>THICKNESS (m)</th>
<th>LITHOLOGY</th>
<th>DEPOSITIONAL CYCLES</th>
<th>SUB UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIASSI</td>
<td>SUDAIR</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>35</td>
<td>KHUFF-A</td>
<td></td>
<td>KHUFF-A Limestone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40</td>
<td>KHUFF-B</td>
<td></td>
<td>KHUFF-B Anhydrite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>45</td>
<td></td>
<td></td>
<td>KHUFF-B Carbonate</td>
</tr>
<tr>
<td>LATE PERMIAN</td>
<td>KHUFF</td>
<td>115</td>
<td>KHUFF-C</td>
<td></td>
<td>KHUFF-C Evapo-dolomites</td>
</tr>
<tr>
<td></td>
<td></td>
<td>65</td>
<td></td>
<td></td>
<td>KHUFF-C Carbonate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>65</td>
<td></td>
<td></td>
<td>KHUFF-D Anhydrite</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100</td>
<td></td>
<td></td>
<td>KHUFF-D Evapo-dolomites</td>
</tr>
<tr>
<td>PERMIAN</td>
<td>UNAYZAH</td>
<td>35</td>
<td></td>
<td></td>
<td>Basal KHUFF Siliciclastics</td>
</tr>
</tbody>
</table>
Rock Description

- **Reservoir samples**: from the Ghawar field, the largest hydrocarbon reservoir in the world producing oil and gas from multi-reservoir zones in the Khuff formation.
- Reservoir samples were obtained from different depths, and their lithology was found to vary. Many samples contained impurities such as anhydrite.
- **Outcrop samples**: from the same formation, outcropping in the Gassim area, Central Province of Saudi Arabia.
Rock Mineralogy (XRD)

Counts

rock origin
- Reservoir (H4309)
- Reservoir (H481)
- Outcrop
Theoretical Background

1. Tensile strength ($\sigma_t$)
For uncracked Brazilian disk:

$$\sigma_t = \frac{2P}{\pi BD}$$

where:

- $P =$ load at failure;
- $B =$ thickness of disk; and
- $D =$ diameter of disk.
2. Mode-I fracture toughness ($K_I$)

For cracked Brazilian disk, Atkinson et al. (1982):

$$K_I = \frac{P}{\sqrt{\pi RB}} N_I$$

where: $K_I = \text{Mode-I stress intensity factor}$;
$R = \text{radius of the Brazilian disk}$;
$B = \text{thickness of the disk}$;
$P = \text{compressive load at failure}$;
$a = \text{half crack length}$; and
$N_I = 1.0$ for pure mode-I.
Experimental Program

• Specimen preparation (Brazilian disks)
  – Reservoir & Outcrop
    D = 100mm (4-inch)
    B = 25.4mm (1-inch)
  – Uncracked & Cracked
    a = 29mm (a/R = 0.3)

• Testing conditions
  – Ambient
  – T = 116°C

• Equipment
Schematic of the Testing Equipment
Experimental Setup for Testing at $T = 116^\circ C$
Results & Discussions

1. Tensile strength ($\sigma_t$) from uncracked Brazilian disk:

1.1 At ambient conditions:

- Outcrop: $\sigma_t = 2.38$ to $2.50$ MPa
- Reservoir: $\sigma_t = 0.88$ to $3.82$ MPa
Variation of Tensile Strength With Depth

Condition
- Ambient
- $T = 116 \, ^\circ C$
Variation of Tensile Strength With Depth

![Graph showing the variation of tensile strength with depth, indicating different conditions and temperatures.](Image)
Variation of Tensile Strength With Depth

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3520</td>
<td></td>
</tr>
<tr>
<td>3550</td>
<td>3480</td>
</tr>
<tr>
<td>3580</td>
<td>3500</td>
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<tr>
<td>3610</td>
<td>3520</td>
</tr>
<tr>
<td>3640</td>
<td>3540</td>
</tr>
<tr>
<td>3670</td>
<td>3560</td>
</tr>
</tbody>
</table>

Condition:
- Ambient
- T = 116 °C
Results & Discussions ... Contd.

1.2 At $T = 116 \, ^\circ C$:

Reservoir:

Ratio of $(\sigma_t)_{116^\circ C}$ to $(\sigma_t)_{ambient} = 0.8$ to $1.38$

$$(\sigma_t)_{116^\circ C} = 1.045 \times (\sigma_t)_{ambient} \quad \text{with } R^2 = 0.961$$
Comparing Tensile Strength at Ambient and Reservoir Temperatures

![Graph showing tensile strength comparison at ambient and reservoir temperatures.](image-url)
Results & Discussions ... Contd.

2. Mode-I fracture toughness ($K_I$) from cracked Brazilian disk:

2.1 At ambient conditions:
   
   Outcrop: $K_I = 0.39$ to $0.47$ MPa m$^{1/2}$
   Reservoir: $K_I = 0.29$ to $1.18$ MPa m$^{1/2}$

2.2 At $T = 116 \, ^\circ \text{C}$:
   
   $K_I$ increased by 25%
Comparing Mode-I Fracture Toughness at Ambient and Reservoir Temperatures
3. Fracture toughness vs. Tensile strength

- For reservoir specimens:
  \[ K_I = 0.3057 \times \sigma_t \], with \( R^2 = 0.946 \)
  Ratio of \( K_I/\sigma_t = 0.4449 \) to 0.1831 \( \text{m}^{1/2} \)

- For outcrop specimens
  Ratio of \( K_I/\sigma_t = 0.1775 \text{ m}^{1/2} \)

- Theoretical value of \( K_I/\sigma_t \) is 0.3070

- Ratios obtained from the data reported by Lim et al. (1994) for various rocks = 0.0752 to 0.2142

- \( K_I/\sigma_t \) Ratio has a unit of (m\(^{1/2}\))
Correlation Between Mode-I Fracture Toughness and Tensile Strength
Conclusions

- Tensile strength ($\sigma_t$) and the fracture toughness ($K_I$) for rock samples from the same formation varied considerably.
- Variation is ascribed to the existence of different members within the same formation.
- $\sigma_t$ varied from 0.88 to 3.82 MPa, more than four times.
- $K_I$ varied from 0.29 to 1.18 MPa m$^{1/2}$, about four times.
- Temperature does not significantly affect the values of $K_I$ and $\sigma_t$. $K_I$ and $\sigma_t$ are slightly higher at higher temperatures.
- $K_I$ is linearly proportional to $\sigma_t$, with an average proportionality constant of 0.3057 m$^{1/2}$.
- $K_I$ can be correlated to the $\sigma_t$.
- Above conclusions are valid for both the outcrop and reservoir samples of the investigated rock.
Thank You.