Evolution of permeability in a natural fracture: Significant role of pressure solution

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Date: 113.05.24

Outline

- Introduction
- Methodology
- Results
- Conclusions

Introduction

- The evolution of the mechanical and transport properties of rocks containing fracture at a variety of scales is strongly influenced by both the mechanical effects of crack formation, dilation, and closure, and their interaction with chemical effects of stress-mediated dissolution and precipitation.

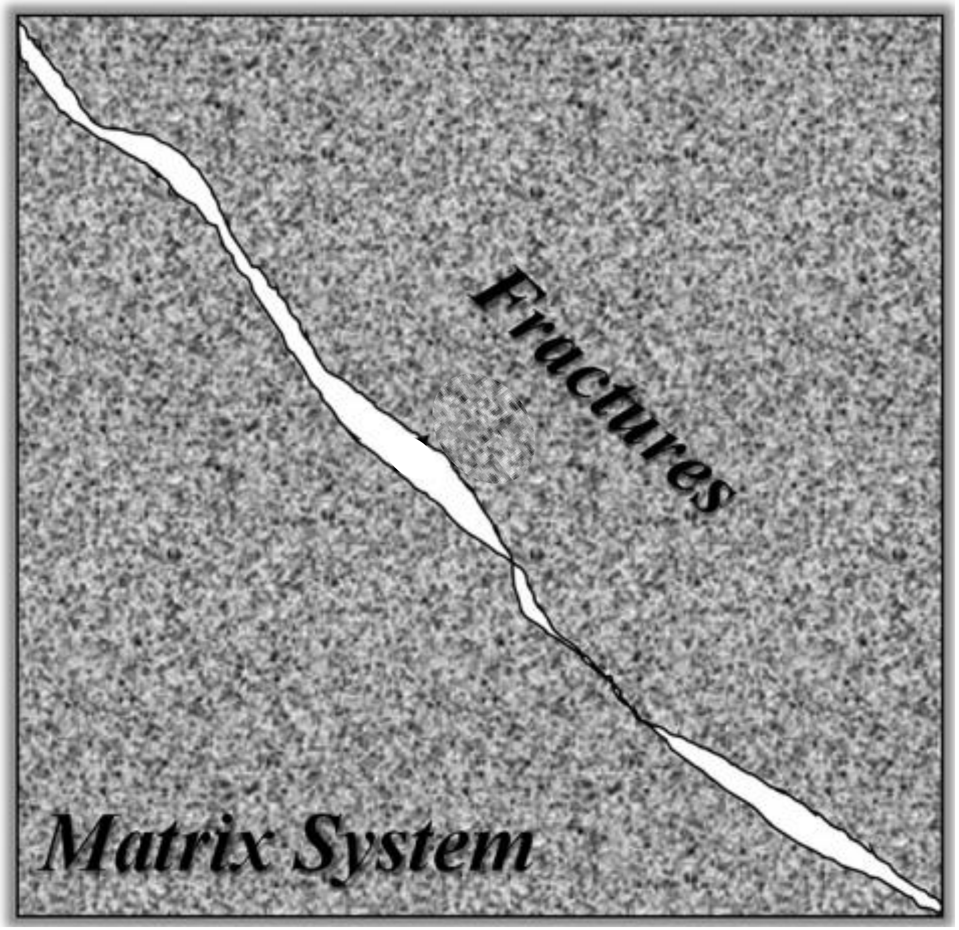
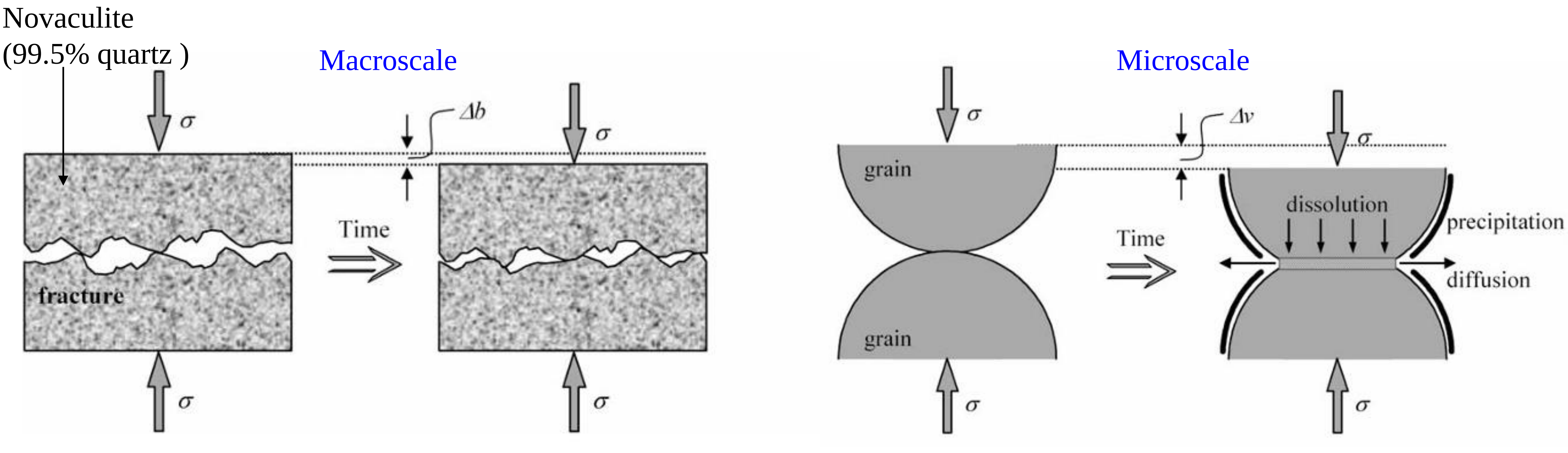


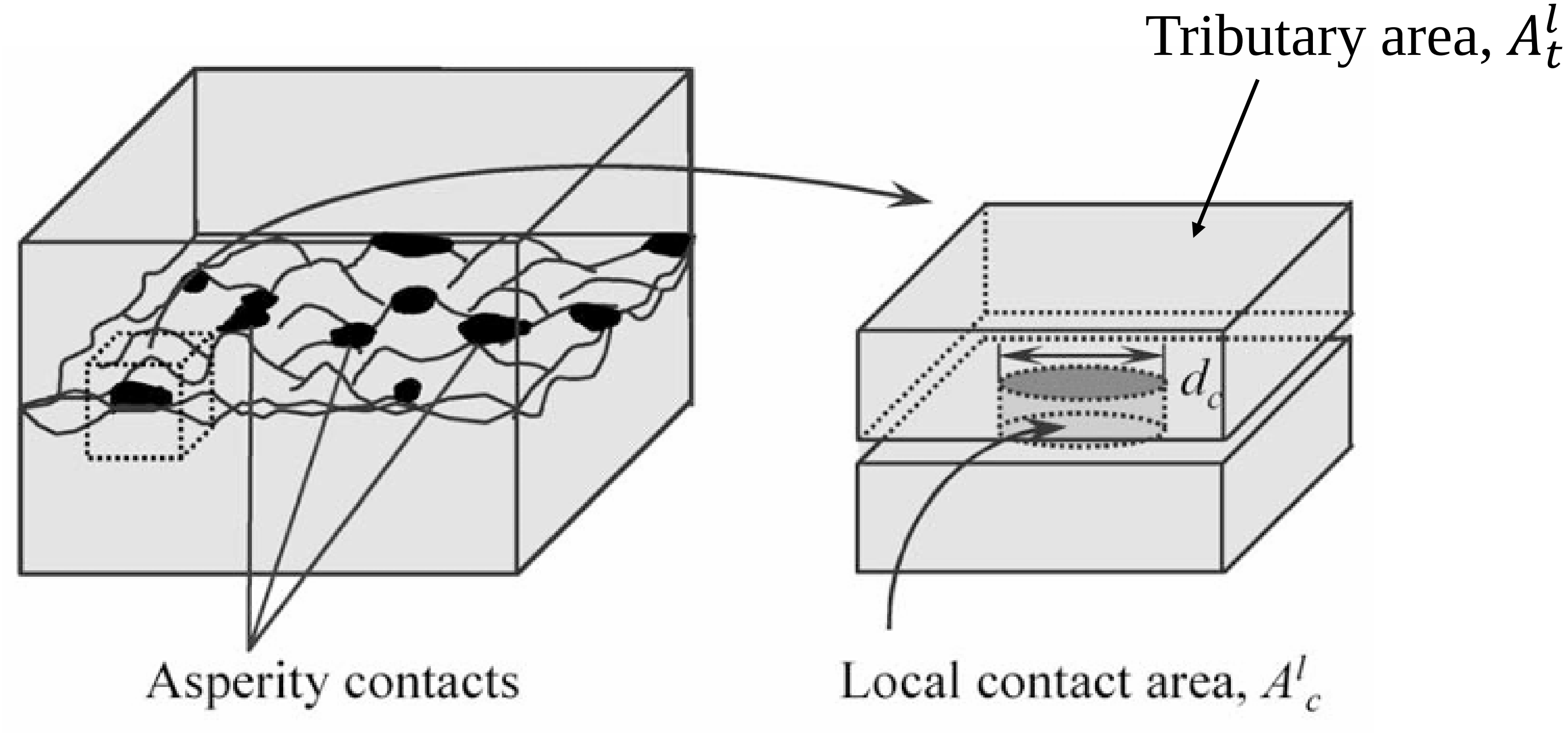
Diagram of fracture in Matrix system. (Song et al., 2023)

- At the contacts the mineral dissolves due to high localized stresses, and dissolved mass diffuses from the interface into the pore space. Finally, precipitation occurs on the free faces of the pore walls.



Schematic of pressure solution for twin contacting grains comprising an aggregate and fractured rock comprising a discontinuity.

- (left) the area of each asperity in contact and considered circular in shape, of diameter, d_c
- (right) A representative contact area, A_c^l



Idealized representation of the asperity contact condition.

Objective

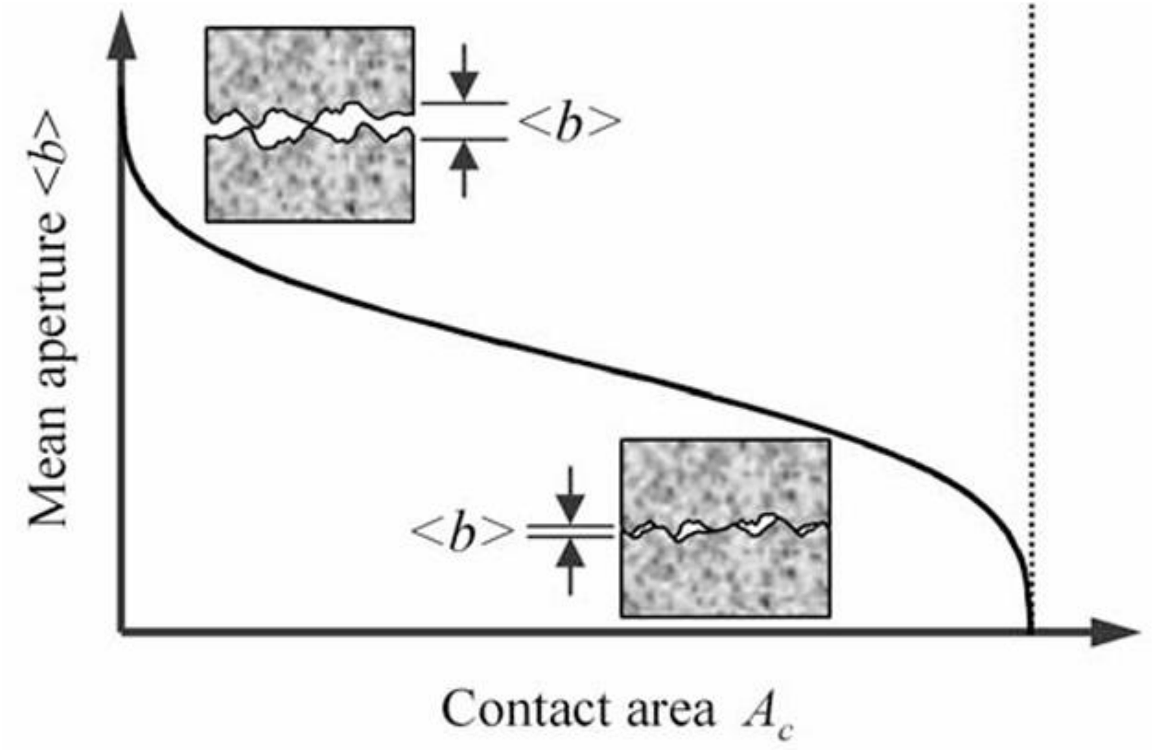
- Applying the measured fracture surface profiles to define simple relations between fracture wall contact area ratio and fracture aperture,and learning the irreversible alteration of the fracture surface geometry during compaction proceeds.

Methodology

The relation is defined by the integral of the Gaussian distribution.

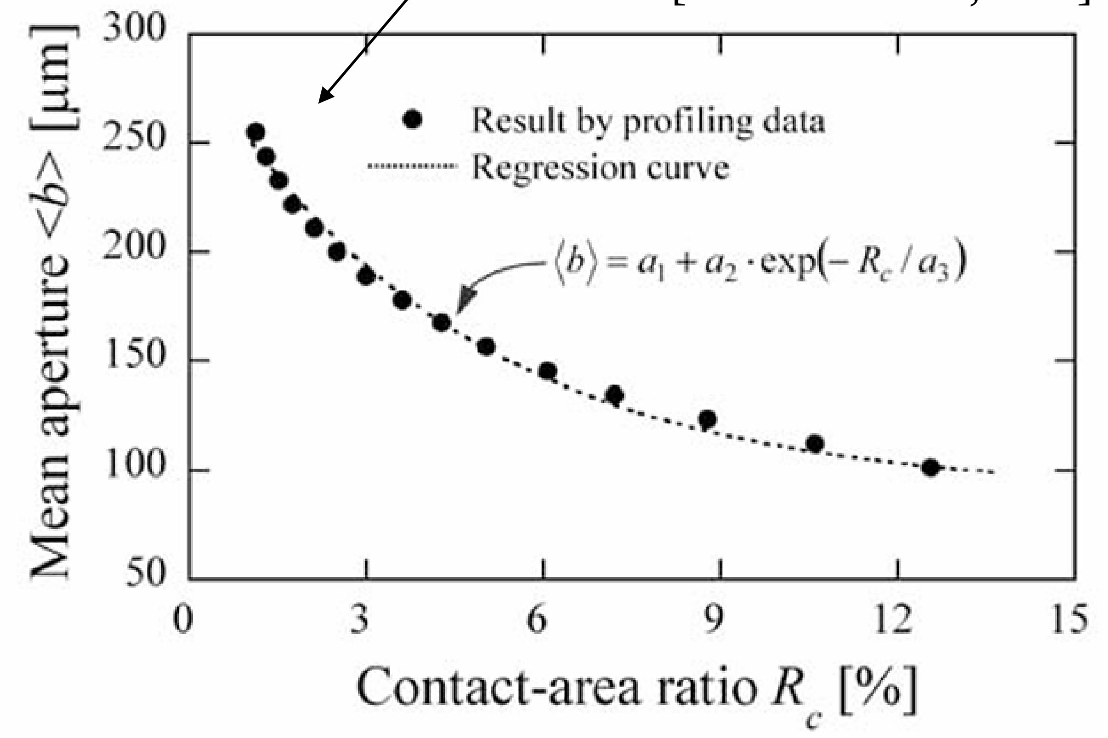
$$\langle b \rangle = 90 + 160 \cdot \exp(-\frac{R_c}{4.46})$$
$$\mathrm{R} > 0.99$$

[Yasuhara et al.,2001]



Relation between mean aperture and contact area of fracture.

[Yasuhara et al.,2001]



Relation between mean aperture and contact area ratio.

➢ Mechanistic compaction model of fracture mediated by Pressure solution

- Dissolution

$$\frac{dM_{\mathrm{diss}}}{dt} = \frac{3\pi V_m^2(\sigma_a - \sigma_c)k_+\rho_g d_c^2}{4RT}$$

where $\sigma_c = \frac{E_m\left(1 - \frac{T}{T_m}\right)}{4V_m}$ $\sigma_a = \sigma_{\mathrm{eff}}\frac{A_t^l}{A_c^l}$ $k_+ = k_+^0 \exp(-E_{k+}/RT)$

- Diffusion

$$\frac{dM_{\mathrm{diff}}}{dt} = \frac{2\pi\omega D_b}{\ln(d_c/2a)}\left(C_{\mathrm{int}} - C_{\mathrm{pore}}\right)$$

where $D_b = D_0 \exp(-E_D/RT)$

- Precipitation

$$\frac{dM_{\mathrm{prec}}}{dt} = V_p\frac{A}{M}k_-\left(C_{\mathrm{pore}} - C_{\mathrm{eq}}\right)$$

where $k_- = k_-^0 \exp(-E_{k-}/RT)$

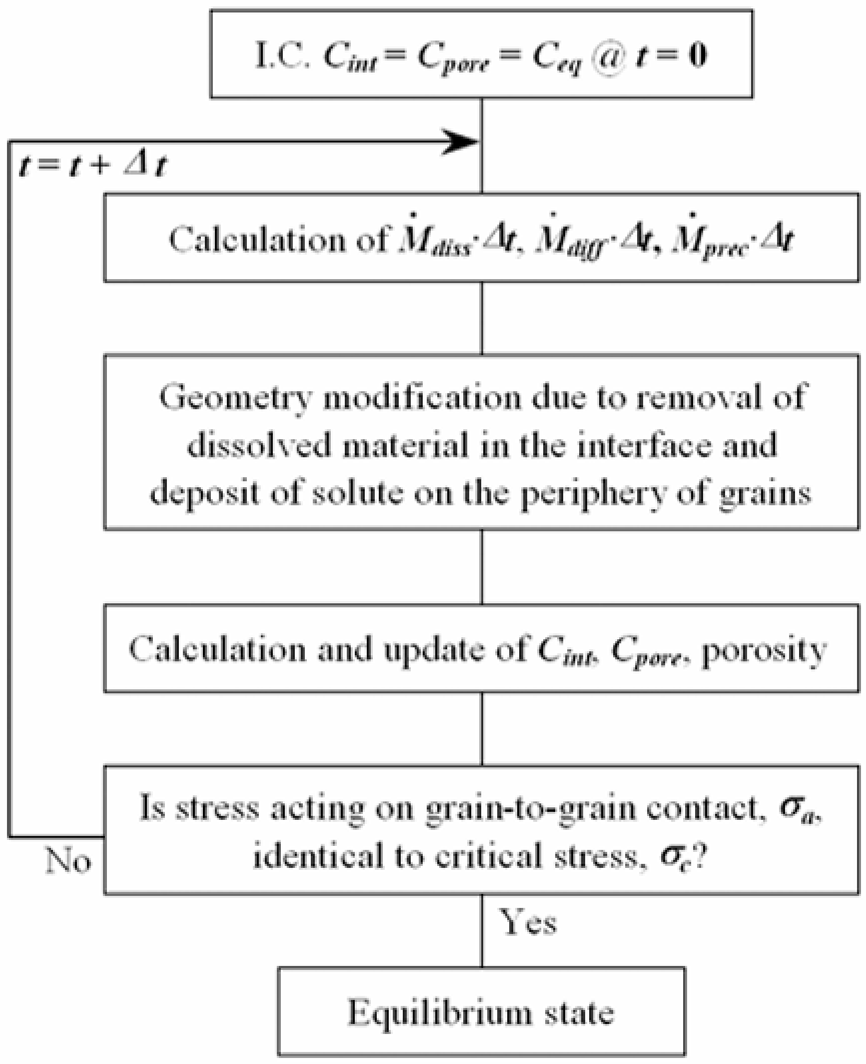
The parameters Where:

A_c^l: contact area
R : gas constant
ρ_g: grain density
A_t^l: tributary area
σ_c : critical stress
E_m : heat of fusion
σ_{eff}: effective stress
D_b: diffusion coefficient
T_m : temperature of fusion
$\frac{dM_{diff}}{dt}$: diffusion mass flux
M: relative mass of the fluid
V_m: molar volume of the solid
$\frac{dM_{diss}}{dt}$: dissolution mass flux
T : temperature of the system
V_p: volume of the fracture void
A: relative fracture surface area
d_c: diameter of the asperity contact
k_+: the dissolution rate constant of the solid
C_{pore}: mineral concentrations in the pore space
C_{int}: mineral concentrations in the interface fluid
C_{eq}: equilibrium solubility of the dissolved mineral
k_-: precipitation rate constant of the dissolved mineral
ω : the thickness of the water film trapped at the interface
$\frac{dM_{prec}}{dt}$: the rate of deposition of solute from the pore space onto the grain surfaces
σ_a: disjoining pressure which the pressure acting at grain – to – grain contacts exceeds the hydrostatic pore pressure.

➢ Mechanistic Compaction Model of Fracture Mediated by Pressure Solution

$$\begin{pmatrix} C_{\mathrm{int}} \\ C_{\mathrm{pore}} \end{pmatrix}_{t+\Delta t} = \begin{bmatrix} D_1 + V_p/4\Delta t & -D_1 \\ -D_1 & D_1 + D_2 + V_p/2\Delta t \end{bmatrix}^{-1} \cdot \left[\begin{pmatrix} dM_{\mathrm{diss}}/dt \\ D_2 C_{\mathrm{eq}} \end{pmatrix}_{t+\Delta t} + \frac{1}{4\Delta t} \begin{bmatrix} V_p & 0 \\ 0 & 2V_p \end{bmatrix} \begin{pmatrix} C_{\mathrm{int}} \\ C_{\mathrm{pore}} \end{pmatrix}_{t} \right]$$

Where $D_1 = \frac{2\pi\varpi D_b}{\ln(d_c/2a)}$, $D_2 = V_p \frac{A}{M} k_-$



Effective Stress σ_{eff}, MPa	Diffusion Path Width ω, nm	Temperature T, °C	Diffusion Coefficient D_b, $m^2\ s^{-1}$	Dissolution Rate Constant k_+, mol $m^{-2}\ s^{-1}$	Critical Stress σ_c, MPa
2.73	4.0	80	5.24×10^{-10}	4.52×10^{-11}	76.7
		120	8.36×10^{-10}	5.35×10^{-10}	74.7
		150	1.12×10^{-9}	2.51×10^{-9}	73.2

Parameters used to represent the experimental results

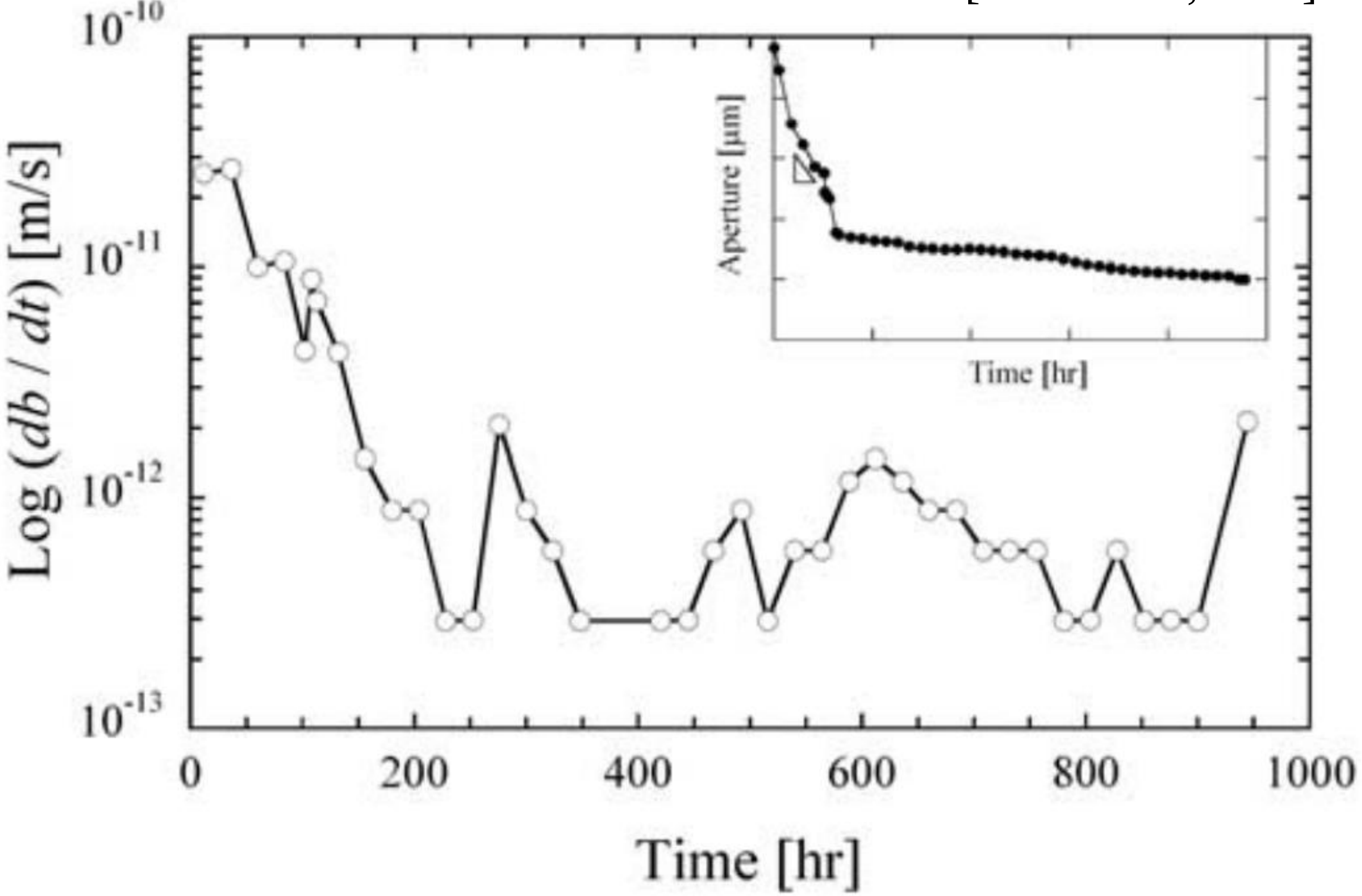
Effective Stress σ_{eff}, MPa	Temperature T, °C	Diffusion Coefficient D_b, $m^2\ s^{-1}$	Dissolution Rate Constant k_+, mol $m^{-2}\ s^{-1}$	Precipitation Rate Constant, k_-, s^{-1}	Critical Stress σ_c, MPa
2.73	80	5.24×10^{-10}	4.52×10^{-11}	8.43×10^{-9}	76.7
5.00	150	1.12×10^{-9}	2.51×10^{-9}	1.42×10^{-7}	73.2
10.00	200	1.68×10^{-9}	2.14×10^{-8}	6.23×10^{-7}	70.7

Parameters used to examine the closure of a fracture under effective stresses in the range 2 – 10 MPa and temperature of 80 – 200°C

Results

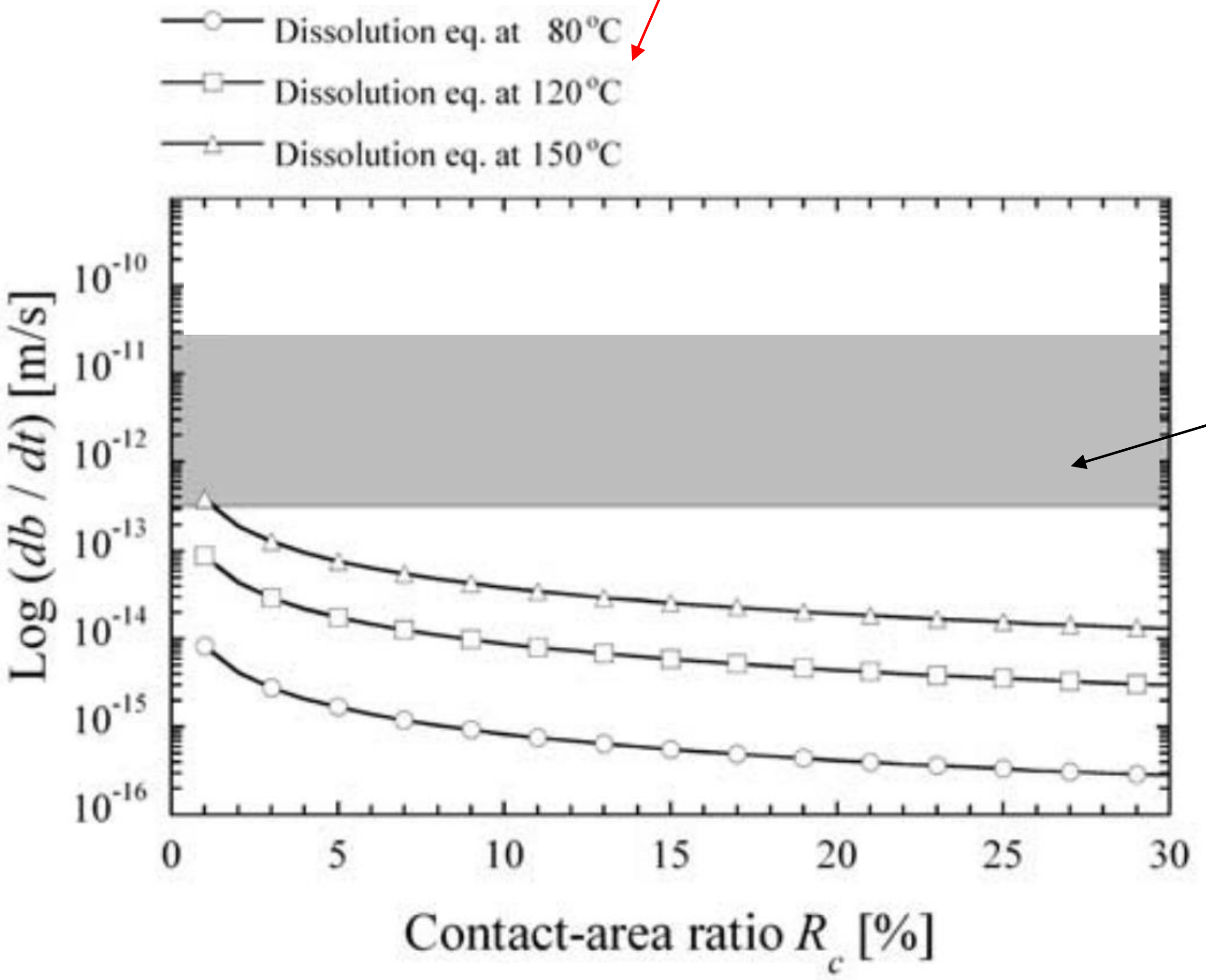
➢ Experimental data

[Polak et al., 2003]



Rate of aperture reduction, db/dt, obtained from the experimental data of aperture change with time.

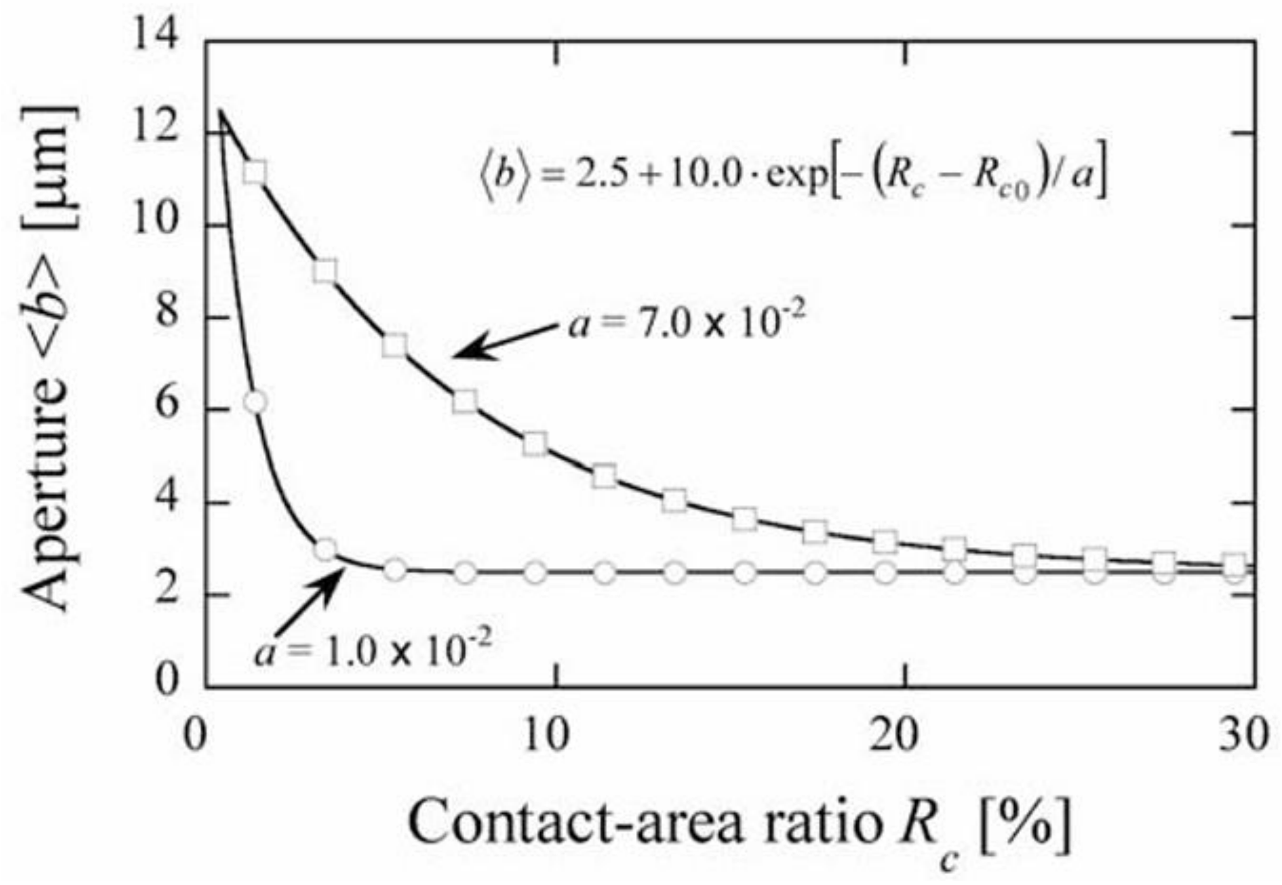
$$\frac{db}{dt} = \frac{dM_{\text{diss}}}{dt}\frac{1}{A_c^l \rho_g} = \frac{3V_m^2(\sigma_a - \sigma_c)k_+}{RT} \approx \frac{3V_m^2 \sigma_a k_+}{RT} = \boxed{\frac{1}{R_c} \cdot \frac{3V_m^2 \sigma_{\text{eff}} k_+}{RT}}$$



Shaded area represents the range of rate of aperture reduction, db/dt, obtained from experimental data. (Polak et al., 2003)

Comparison of the relation between rate of aperture reduction, db/dt and contact area ratio.

- The curve with circles shows a sharper reduction of aperture with an increase of contact area than the relation represented by the squares.



Relation between aperture and contact area ratio.

$$\frac{db}{dt} = \frac{dM_{\text{diss}}}{dt}\frac{1}{A_c^l \rho_g}$$

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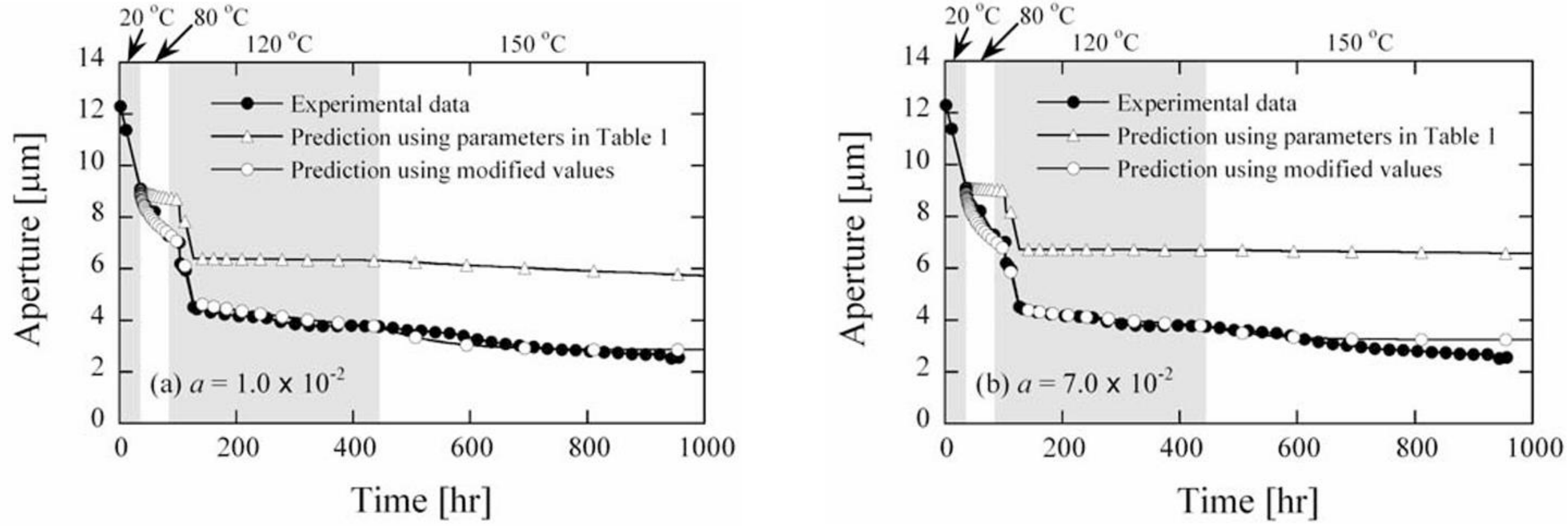
$$\frac{dM_{\text{diss}}}{dt} = \frac{3\pi V_m^2(\sigma_a - \sigma_c)k_+\rho_g d_c^2}{4RT}$$

Modified

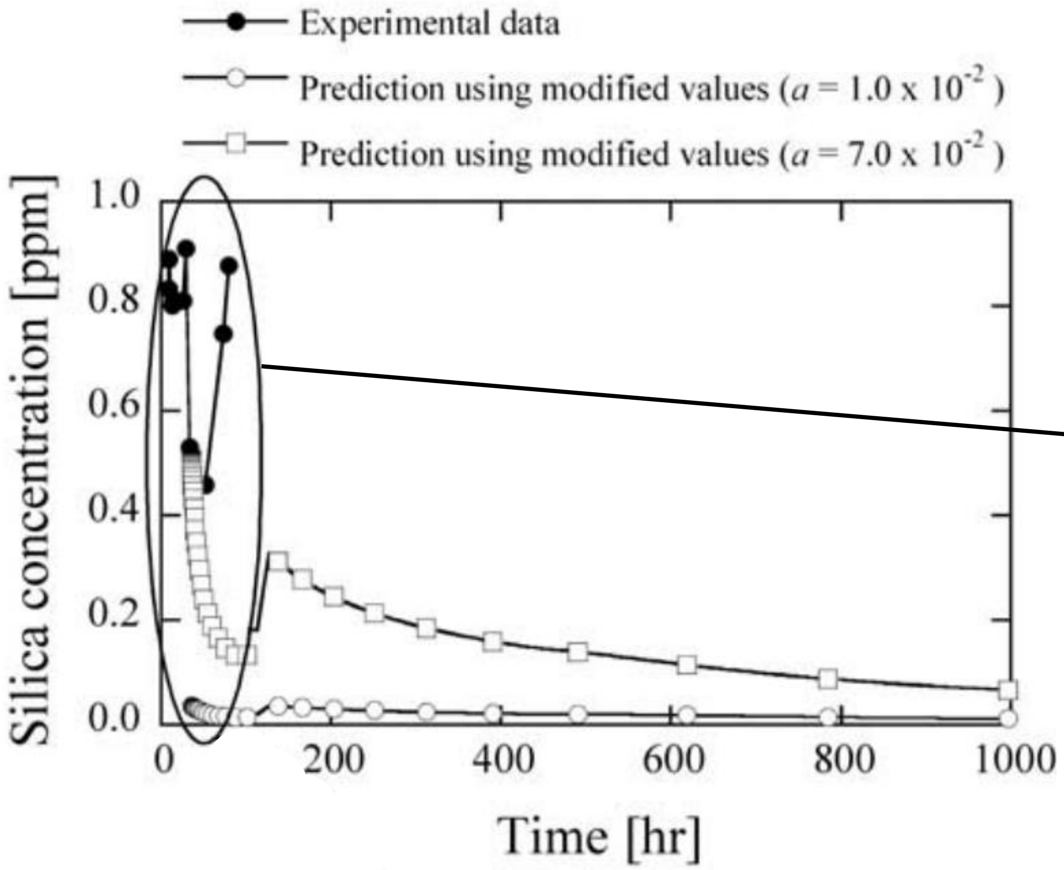
$$\frac{dM_{\text{diss}}}{dt} = \boxed{f_r}\frac{3\pi V_m^2(\sigma_a - \sigma_c)k_+\rho_g d_c^2}{4RT}$$

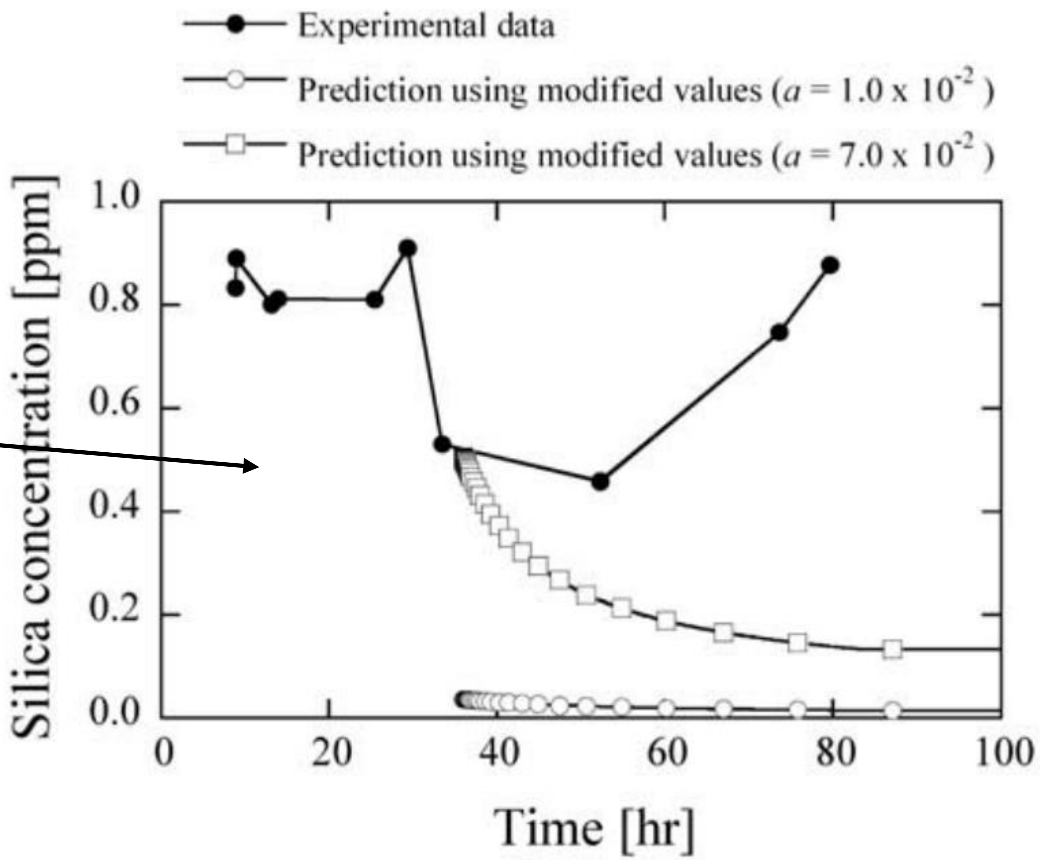
- In order to obtain more realistic predictions, the fracture surface areas should be evaluated microscopically. Therefore they introduce a roughness factor, f_r

$$f_r = \frac{\text{true surface area (microscopic)}}{\text{apparent surface area (macroscopic)}}$$

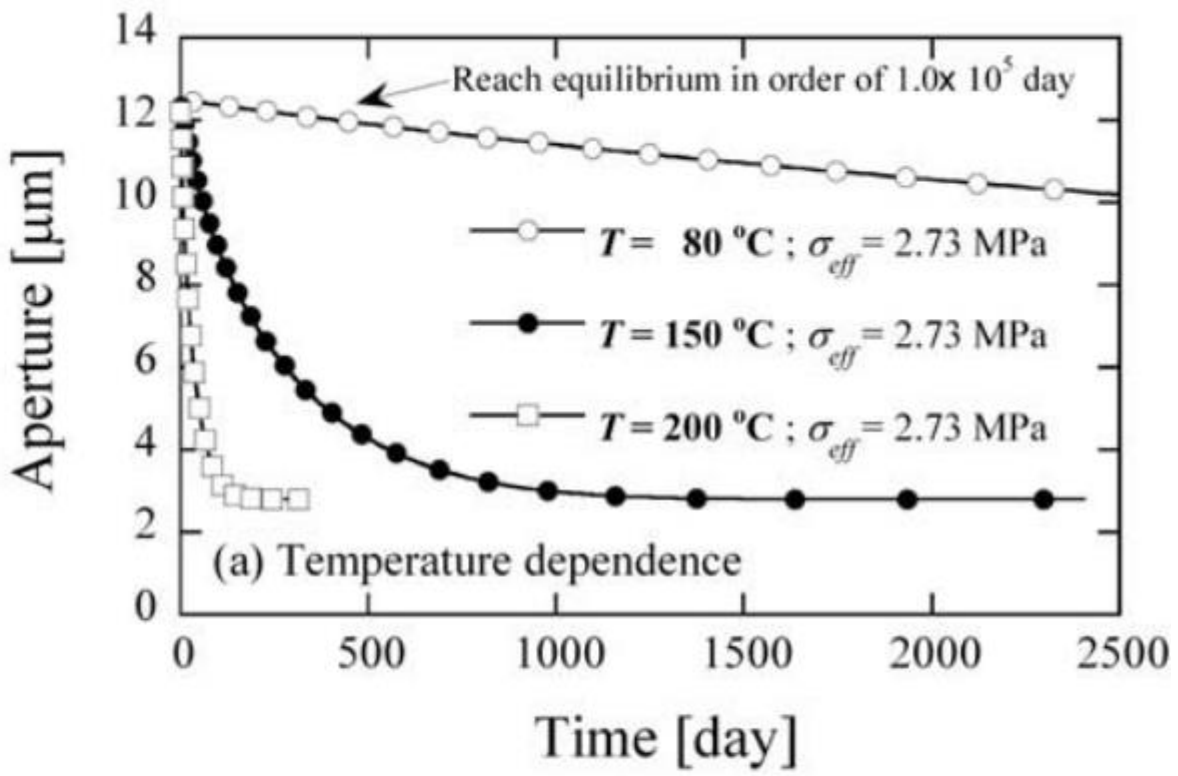


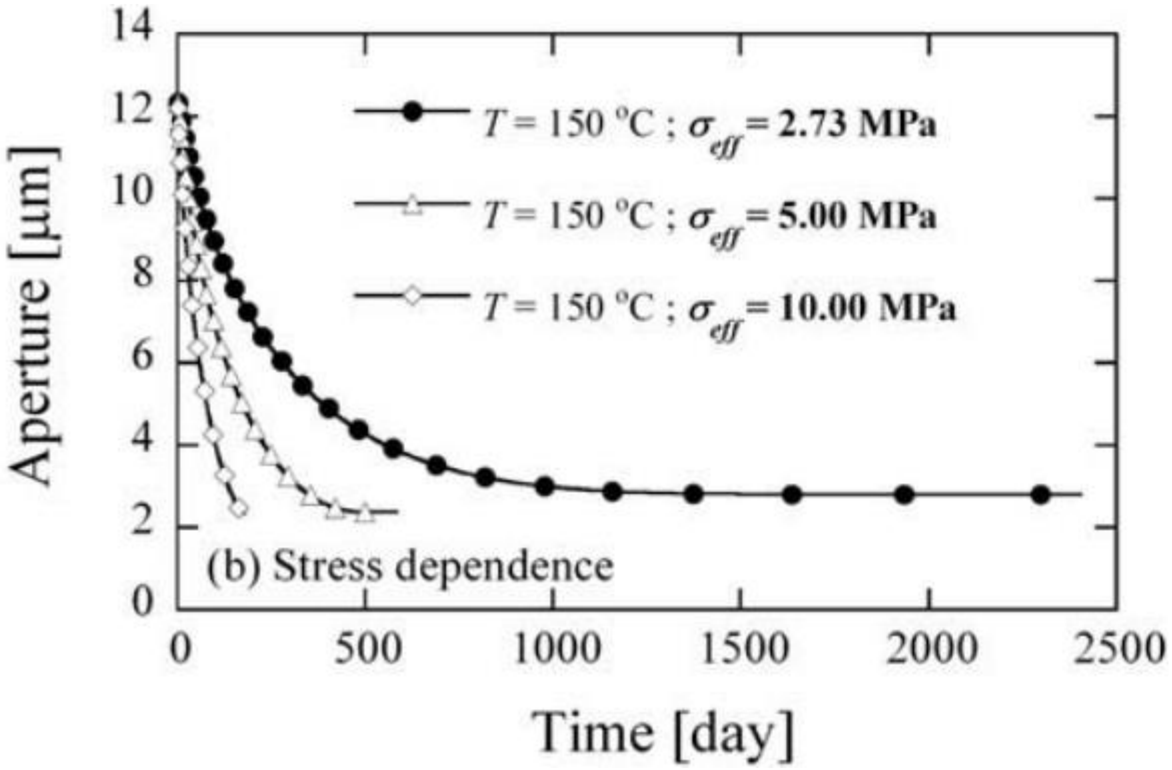
Comparison of aperture reduction with time between experimental data of Polak et al. [2003] and predictions of the current model.





Comparison of change of silica concentration with time between experimental data of Polak et al. [2003] and predictions of our model.





Predictions of aperture reduction in a fracture with time under various system conditions of (a) temperature and (b) effective stress.

1. Even a roughness factor is added to modified for the unmatch between macro and micro contact areas. The concentration of sillica is still not as expected, which may be due to the neglect of free surface dissolution.

2. According to the results, temperature is the main controlling factor. With temperatures in the range 80-200 ◦C, the completion time for fracture reduction decreases from centuries to approximately one year; while in the effective stress range 3-10 MPa, it decreases from several years to less than a year .

Thank you for listening !