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Understanding Chemically-Assisted Fracture in Porous Media Using Phase-Filed Fracture Technique

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1. Introduction

Predicting and controlling fractures in subsurface has posed many challenges in understanding the long-term performance of many geological systems such as CO_2 sequestration, geothermal, waste repositories, oil and gas recoveries, etc. In most of these applications, interaction between the native and injected fluids with rock minerals leads to chemical alteration within the fractured rock formation. Such chemical alterations lead to change in the properties of fracture and rock strength [1-2]. Many studies have studied the impact of pre-existing and faults fractures within geological system [3-5], but this study focuses on fracture initiation and propagation and shows how the state-of-the-art phase-field fracture can be used to model chemically-assisted fracture in geological systems. In this formulation, we introduced a chemical damage parameter which is linked to the porosity of rock formation.

2. Phase-Field Fracture Technique

The foundational idea of the phase-field fracture method is to approximate a discontinuity Γ by a smeared surface.

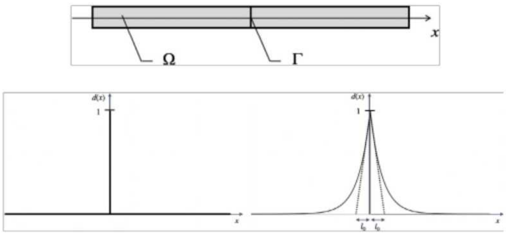

Figure 1 (a) Illustration of crack in one-dimensional domain. (b) crack discontinuity and regularization over l_0 [6].

In the phase-field fracture technique, the potential total energy is defined by:

$$\psi = \underbrace{\int_{\Omega} g(\phi)\psi_0(\varepsilon)\ \mathrm{d}\Omega}_{\psi^{\mathbf{u}}} + \underbrace{\int_{\Omega} \gamma_{l_0}(\phi, \nabla\phi) g_c\ \mathrm{d}\Gamma}_{\psi^{\phi}}$$

where the integral of γ_{lo} represents the crack surface and $g(\phi)$ is the degradation function.

3. Chemical Damage

In order to include chemical damage at the crack tip, we have introduced an additional damage parameter, d^{chem}, which depends on the change in the porosity and is defined as:

$$d^{che} = 1 - e^{-r\Phi}$$

To account for the chemical damage parameter, the strain energy formulation needs to be revised as:

$$\psi(\varepsilon, d, d^{che}) = [(1 - d^{che})(1 - d)^2 + k]\psi_0(\varepsilon)$$

where ψ_o is the initial strain energy and k is the stability parameter that was used in the degradation function.

To solve for the chemical damage parameter, diffusion equation should be solved.

$$\begin{cases} \frac{\partial c}{\partial t} + div(\mathbf{q}) = 0 \\ \mathbf{q} = -Dgrad(c) + \frac{DV}{RT} c \nabla \sigma_H \end{cases}$$

where c is the concentration, q is the flux term, D is the diffusion coefficient, R is the gas constant, T is the temperature, V is the partial molar volume of injected gas in water, and σ_H is the hydrostatic stress.

As the crack initiates and propagates, there will be changes in both chemical and mechanical damages leading to changes in both porosity and diffusion coefficient. Since the chemical damage is related to the change in the porosity, therefore, the diffusion coefficient needs to be updated as a function of both porosity and mechanical damage. To be conservative, the maximum change in the diffusion coefficient was used in each timestep.

4. Case Study

To illustrate the importance of chemical-damage in predicting fracture behaviour, three different rock formations (e.g., sandstone, limestone, and shale) exposed to supercritical CO_2 were studied here. We used the classical single-edge crack problem shown in Figure 2 for our case study. The evolution of the crack at different displacement is shown in Figure 3, which also highlights the highest value of CO_2 concentration occurring at the crack tip.

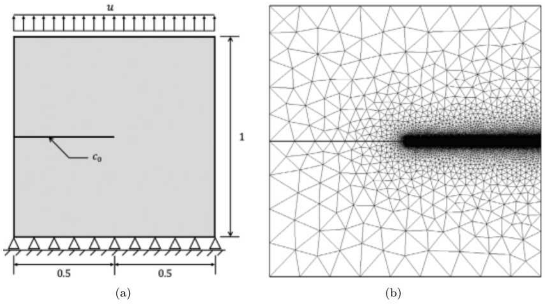

Figure 2 Schematic of single-edge crack problem.

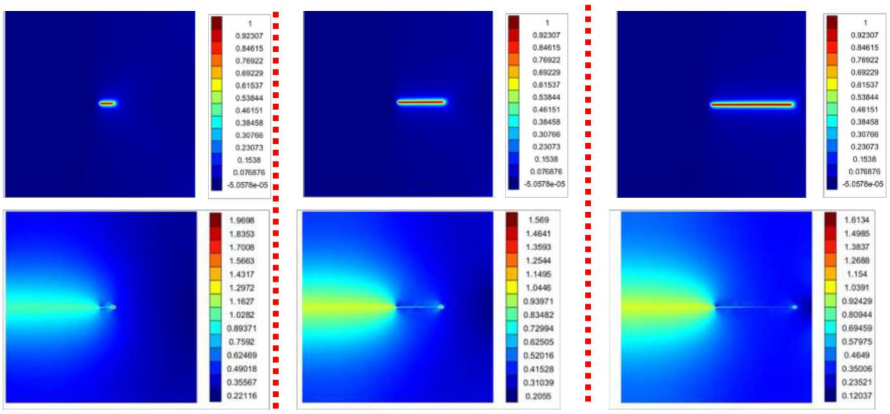

Figure 3 Illustration of evolution of mechanical damage (top figures) and concentration of CO_2 (bottom figures) at the crack tip at different loading time [6].

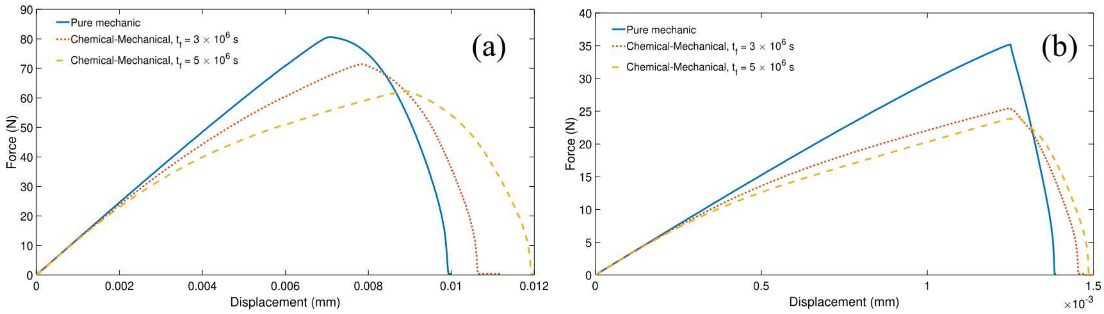

Figure 4 Load-displacement curves with just mechanical and chemo-mechanical degradation at two exposure time of 3 × 10^6 s (red line) and 5 × 10^6 s (yellow line) for (a) sandstone, (b) shale [6].

Figure 4 shows that the results of dissolution in both sandstone and shale are noticeable compared with a case in which only mechanical damage was considered. However, as exposure time increases, there is a more pronounced change in the load-displacement curve in sandstone versus shale. This is mainly due to the properties of different rocks and in this case lower diffusion coefficient in shale led to less drop in the peak load at longer exposure time. Moreover, Figure 5 shows how the chemical damage is more localized in shale comparing with limestone.

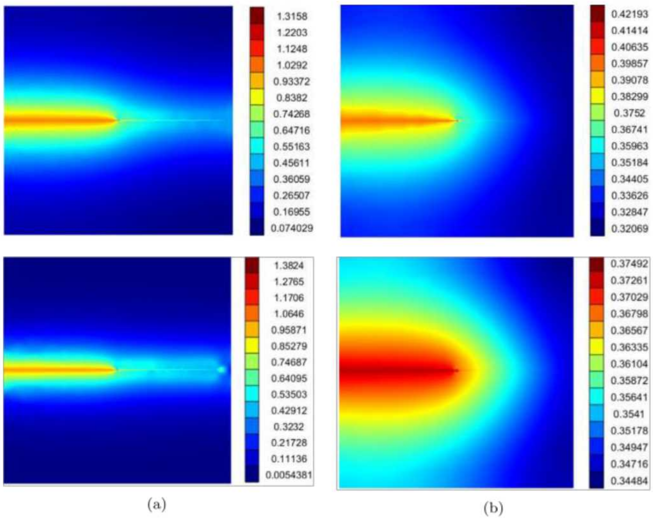

Figure 5 Illustration of concentration and chemical damage for (a) limestone, (b) shale [6].

5. Conclusions

- This formulation highlights that our modified phase-filed fracture formulation can account for the chemical damage in addition to the mechanical damage.

- Chemo-mechanical formulation coupled with the phase-filed fracture method enabled us to investigate chemically-driven fracture in sandstone, limestone, and shale due to exposure to CO_2.

- Chemical damage is more localized in shale compared with sandstone and limestone.

References

[1] Newell P. Ilgen A.G., Science of Carbon Storage in Deep Saline Formations, Process Coupling across Time and Spatial Scales, 2018.

[2] Laubach S.E., Lander R.H., Criscenti L.J., Anovitz L.M., Urai J.L., Pollyea R.M., Hooker J.N., Narr W., Evans M.A., Kerisit S.N., Olson J.E., Dewers T., Fisher D., Bodnar R., Evans B., Dove P., Bonnell L.M., Marder M.P., Pyrak-Nolte L., The Role of Chemistry in Fracture Pattern Development and Opportunities to Advance Interpretations of Geological Materials, Reviews of Geophysics, 2019, https://doi.org/10.1029/2019RG000671.

[3] Rutqvist J., Stephansson O., The role of hydromechanical coupling in fractured rock engineering, Hydrogeology Journal 11 (1), 7-40, 2003.

[4] Martinez M.J., Stone C.M., Notz P.K., Turner D.Z., Hopkins P.L., Subia S., et al., Computational thermal, chemical, fluid, and solid mechanics for geosystems management Sandia Report SAND2011-6643, 2011.

[5] Newell P., Martinez M.J., Eichhubl P., Impact of layer thickness and well orientation on caprock integrity for geologic carbon storage, Journal of Petroleum Science and Engineering 155, 100-108, 2017

[6] Schuler L., Ilgen A.G., Newell P., Chemo-mechanical phase-field modeling of dissolution-assisted fracture, Computer Methods in Applied Mechanics and Engineering 362, 112838, 2020.

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