Phase-Field Modeling of Fluid-Driven Fracture in Porous Media with Application to Desiccation Cracking

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Abstract

Desiccation cracking due to fluid pressure reduction is a key issue in porous media. We study this phenomenon using a phase-field model (PFM) coupled with Biot's poroelastic theory to formulate a constitutive framework for desiccation-driven fracture and its associated energy dissipation. Fluid transport is described by a modified consolidation model with damage-dependent intrinsic permeability following an Arrhenius-type law, where the activation energy decreases with the damage variable z. The resulting system comprises the momentum balance, crack evolution, and fluid mass balance equations, written as follows.

$$\begin{cases} -\operatorname{div}(\sigma_z^\dagger[u,\varrho]) = 0 & \text{in } \Omega, \\ \alpha \dfrac{\partial z}{\partial t} = \Big(\epsilon \operatorname{div}(\gamma_* \nabla z) - \dfrac{\gamma_*}{\epsilon} z + (1-z)\lambda^* (\operatorname{div} u)_+^2 + 2\mu |e_D[u]|^2\Big)_+ & \text{in } \Omega, \\ \dfrac{1}{Q}\dfrac{\partial \varrho}{\partial t} = \operatorname{div}\big(\kappa^\dagger(z,\epsilon)\nabla\varrho\big) - \alpha_p (1-z)^2 \operatorname{div}\dot{u} & \text{in } \Omega. \end{cases}$$

For the numerical implementation, we employ FEM with P1 elements and adaptive mesh refinement to resolve crack evolution in two-dimensional settings. A semi-implicit time discretization is used to solve the coupled nonlinear system. Numerical results show that the model captures the initiation and propagation of desiccation cracks, as well as the strong coupling between fluid pressure and damage evolution in porous media.

Keywords: Poroelasticity, Desiccation Cracking, Phase Field Model, Anisotropic Adaptive Mesh, Arrhenius law, Random Heterogeneous Materials.

References

[1] Biot, M. A. (1941). General theory of three-dimensional consolidation. Journal of Applied Physics, 12(2), 155-164.

[2] Kimura, M., Takaishi, T., Alfat, S., Nakano, T., & Tanaka, Y. (2021). Irreversible phase field models for crack growth in industrial applications: thermal stress, viscoelasticity, hydrogen embrittlement. SN Applied Sciences, 3(9), 781.

[3] S. Alfat, M. Beneš, J. F. T. Rabago, and M. Kimura Energy-Consistent Phase Field Model for Fluid-Driven Fracture in Porous Medium: Part I. Hydraulic Fracturing. On Preparation.