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Mechanics of Materials

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A three-scale poromechanical model for swelling porous media incorporating solvation forces: Application to enhanced coalbed methane recovery

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ARTICLE INFO

Keywords:

Swelling porous media
Poromechanics
Homogenization
Density functional theory
Solvation force
Enhanced coalbed methane recovery

ABSTRACT

In this work we develop an innovative three-scale poromechanical model for expansive porous media characterized by two levels of porosity associated with nano and macropores (or fissures). New versions of the effective stress principle and the constitutive law for the Lagrangian porosity are rigorously reconstructed within the framework of the formal homogenization procedure in the upscaling of the anomalous behavior of a fluid mixture in the nanopores. Local adsorption isotherms are computed within the framework of Thermodynamics of inhomogeneous fluids in nanopores by exploring the tools of the Density Functional Theory (DFT) for calculating fluid density profiles based on the minimization of grand canonical potential under uniformity of the chemical potential. At the microscale, a modified form of the effective stress principle is derived incorporating the disjoining pressure effects. By linearizing the poromechanics around a reference state, the microscopic governing equations are rephrased in the framework of an incremental nonlinear elastic formulation with coefficients strongly dependent on the disjoining pressure. The poromechanics of the matrix is then homogenized with the macropore/fissure network giving rise to a new three-scale model ruled by the effective stress, Lagrangian porosity and permeability. Within the framework of DFT, the profiles of structural component of the disjoining pressure and partition coefficient are numerically constructed for a binary mixture of CH₄/CO₂ in the nanopores of an organic matter aiming application to enhanced coalbed methane recovery. Computational simulations illustrate the behavior of the effective coefficients. Among the numerical results we highlight the appearance of two regimes of closure and mild-opening of the cleats strongly dependent on the CO₂-partial pressure.

1. Introduction

A wide class of swelling porous media including clays, organic shales, polymers, coal and biological tissues are characterized by several networks of pores Le et al. (2015, 2016, 2017); Nikoosokhan et al. (2014) and Wu et al. (2010). In particular we highlight the finer structure of nanopores usually filled by fluids in an anomalous state together with a larger network of macropores (or fissures) where the thermodynamic properties of the fluids are associated with the homogeneous bulk state, unaffected by the distance to the solid (Fig. 1). Such a class of systems exhibits a typical signature associated with the presence of co-existing substructures with strong mutual interactions along with multimodal pore-size distributions where the nanopore network plays an important role in fluid storage whereas the larger voids provide pathways for fluid percolation (Murad

and Moyne, 2008; Le et al., 2015; 2016; 2017). The common form of microstructure underlying swelling systems is characterized by a hierarchy of three natural scales. The finest scale is the nanoscale wherein the porous fabric consists of an assembly of very tiny pores where fluid properties are strongly perturbed by the solid in the form of confinement (hard sphere), physico-chemical and/or electro-chemical effects. Owing to the interplay between solid and fluid interactions, the nanoconfinement induces perturbations in the fluid molecular configuration leading to a redistribution of particles governed by the structural correlation functions (Hansen and McDonald, 2006). At the microscale (the homogenized nanoscale), the solid-fluid mixture is envisioned as overlaying continua forming the homogenized expansive matrix with interactions represented in an averaged fashion at each point. Moreover, the matrix is commonly inter-winded by the network of macropores (or fissures) giving rise to a three-scale effective medium

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<https://doi.org/10.1016/j.mechmat.2019.01.021>

Received 14 August 2018; Received in revised form 22 January 2019; Accepted 28 January 2019

Available online 29 January 2019

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