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Multi-scale modeling of time-dependent behavior of claystones with a viscoplastic compressible porous matrix

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ABSTRACT

This paper is devoted to multi-scale modeling of time-dependent behavior of claystones using a two-step homogenization procedure. Two materials scales are considered. At the mesoscopic scale, the material is constituted by a clay matrix and embedded mineral grains. At the microscopic scale, the clay matrix is a porous medium composed of a solid phase and spherical pores. The macroscopic plastic criterion of the clay matrix is first determined by a modified secant method (Maghous et al., 2009) considering a pressure sensitive yield function for the solid phase. This criterion is then used as the loading function for the description of viscoplastic deformation of the clay matrix, together with a non-associated viscoplastic potential. At the second step of homogenization, the macroscopic behavior of the claystone is determined by taking into account the effect of mineral grains (quartz and calcite). For this purpose, we propose an extension of the incremental approach initially proposed by (Hill, 1965) to modeling of time-dependent behavior. Therefore, the micromechanical model is able to explicitly account for the effects of pores and mineral grains at two different scales. The numerical algorithm for numerical implementation of the micromechanical model is also presented. The proposed model is finally verified through comparisons between numerical results and experimental data in triaxial compression tests with constant strain rate and in triaxial creep tests.

1. Introduction

Claystones or hard clayey rocks have been investigated in many countries in the context of feasibility study for geological disposal of radioactive wastes. Due to their low permeability, relatively high mechanical strength and the absence of major tectonic fractures, these clayey rocks are envisaged as one of potential geological barriers. In this context, it is necessary to conduct investigations on both short and long term thermo-hydro-mechanical behavior of these materials. An extensive research program has being conducted by the French National Agency for radioactive wastes management (Andra) involving both experimental investigations and constitutive modeling of the Callovo-Oxfordian (COx) argillite (Lebon and Mouroux, 1999). The mineralogical analysis has revealed that at a mesoscopic scale this clayey rock is composed of a quasi-continuous clay matrix in which are embedded mineral inclusions, mainly quartz and calcite grains (see Fig. 1, Robinet, 2008). But at a microscopic scale, the clay matrix is a porous medium which is constituted by solid clay particles and pores between such particles. This inter-particle porosity constitutes the main porosity of the argillite (Fig. 2). On the other hand, a series of laboratory tests have been conducted on argillite samples with different mineralogical compositions, under different saturation degree and temperature (Chiarelli et al., 2003;

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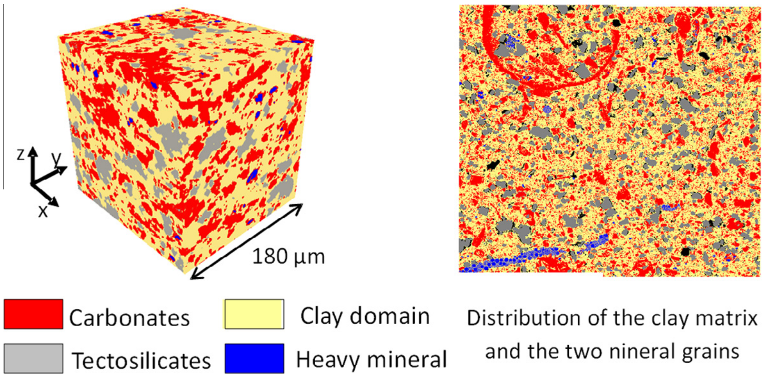

Fig. 1. Microstructure of the COx argillite at the meso-scale (Robinet, 2008).

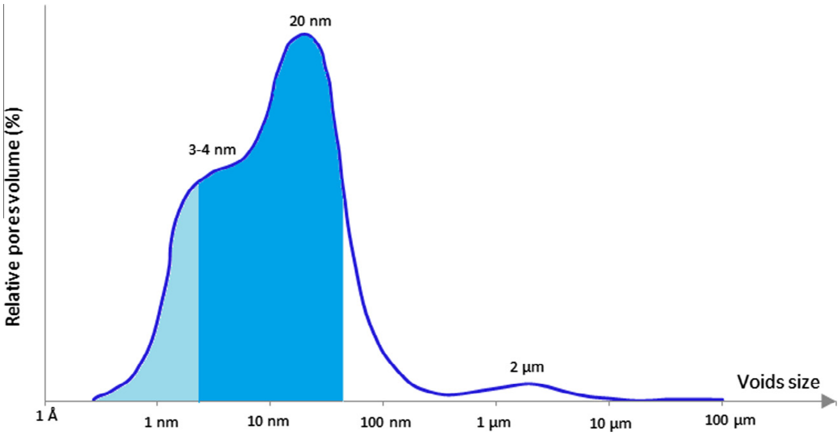

Fig. 2. Distribution of pore size in COx argillite (Andra, 2005).

Hu et al., 2014a,b). Some mechanical and hydromechanical tests were associated with microscopic analysis of local strain distribution inside argillite samples (Bornert et al., 2010; Yang et al., 2012). The experimental data have shown that the mechanical behavior of argillite exhibited significant inelastic deformation. The local strain field at the mesoscopic scale is strongly heterogeneous and microcracks are developed both at inclusion/matrix interfaces and inside the clay matrix. Moreover, the mechanical behavior is clearly influenced by the mineralogical composition. Due to the presence of clay minerals as smectite, the mechanical behavior of argillite is also strongly sensitive to the variation of water saturation degree.

Based on the experimental results and using the irreversible thermodynamics framework, different macroscopic constitutive models have been formulated to describe the mechanical behavior of argillite in both saturated and partially saturated conditions (Chiarelli et al., 2003; Shao et al., 2006; Hoxha et al., 2007; Jia et al., 2010). These models are generally able to reproduce the main features of the mechanical behavior of argillite observed in macroscopic tests. However, they fail to account for the strain heterogeneity in the different constituents and the effects of mineralogical composition and porosity. During the last decade, significant advances have been obtained on multi-scale modeling of both brittle and ductile geomaterials. Concerning clayey rocks, Abou-Chakra Guery et al. (2008) have proposed a micromechanical model for the Callovo-Oxfordian (COx) argillite based on an extension of the incremental approach initially proposed by Hill (1965) for metal materials and composites (Doghri and Ouaar, 2003; Chaboche and Kanoute, 2005). In this model, the argillite was considered as a three-phase composite constituted by the clay matrix, calcite, and quartz grains. The clay matrix was seen as a homogeneous solid material obeying the classical Drucker–Prager type plastic model. Therefore the inter-particular porosity inside the clay matrix was neglected. This model was further extended to the time-dependent deformation of argillite by the same authors (Abou-Chakra Guery et al., 2009; Huang and Shao, 2013), always neglecting the porosity effect. Recently, Shen et al. (2012) have extended the previous model by considering the clay matrix as a porous medium at the microscopic scale. Based on a first-step homogenization procedure, the effective plastic model for the clay matrix explicitly depends on the porosity. The macroscopic behavior of argillite was also determined using the extended Hill's incremental method. On the other hand, Shen et al. (2013) have obtained a closed-form macroscopic plastic criterion by using a modified secant