International Journal of Plasticity 69 (2015) 73–88

Contents lists available at ScienceDirect

International Journal of Plasticity

journal homepage: www.elsevier.com/locate/ijplas

A micro-macro model for time-dependent behavior of clayey rocks due to anisotropic propagation of microcracks

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ARTICLE INFO

Article history:
Received 4 July 2014
Received in revised form 25 October 2014
Available online 12 February 2015

Keywords:
Time-dependent damage
Creep
Microcracks
Micromechanics
Homogenization
Clayey rocks

ABSTRACT

In this paper, a micro-macro model is proposed for the time-dependent behavior of clayey rocks. Two material scales are considered. At the mesoscopic scale, the studied material is represented by a three-phase composite. Quartz and calcite grains are embedded inside the clay matrix. At the microscopic scale, the clay matrix is characterized by a cracked elastic solid. The creep deformation is assumed to be induced by the time-dependent propagation of anisotropic microcracks inside the clay matrix. A two-step homogenization procedure is proposed. The effective elastic properties of the cracked clay matrix are first determined using an Eshelby solution based homogenization method. Two different homogenization schemes are used respectively with and without taking into account crack interactions. Then the macroscopic mechanical properties of heterogeneous clayey rocks are determined by the second homogenization step using the Mori Tanaka Scheme. A sensitivity study is performed in order to evaluate macroscopic consequences of the microscopic time-dependent propagation law of microcracks. Finally, comparisons between numerical results and experimental data from creep tests are presented.

1. Introduction

In the context of geological disposal of radioactive waste, clayey rocks have been largely investigated in many countries as a potential geological barrier. In France, under the coordination of the French National Agency for radioactive waste management (Andra), an underground research laboratory (URL) is constructed in Bure in the North-East region of France, in the geological layers of Callovo-Oxfordian argillites (Cox) at a depth of 445 m–490 m (Lebon and Mouroux, 1999). A series of laboratory tests and in situ experiments have been performed for the characterization of thermo-hydromechanical properties of the Cox argillites (Yang et al., 2010, 2012; Hu et al., 2014a, 2014b). According to the mineralogical analyses (Chiarelli et al., 2003; Robinet, 2008 and others), the average mineralogical compositions of Cox argillite are of 45% clay minerals, 28% calcite, 22% quartz and less than 5% other minerals (feldspars, pyrite etc.). These clayey rocks are characterized by complex and multi-scale microstructures (Robinet, 2008). However, as a first approximation and in view of micro-macro modeling, two relevant material scales should be taken into account (Abou-Chakra et al., 2008; Robinet, 2008; Shen et al., 2012). At the mesoscopic scale as illustrated in Fig. 1, the Cox argillites can be seen as a three-phase composite constituted by a clay matrix in which are embedded calcite and quartz grains. At the microscopic scale, the clay matrix is a porous material composed by a solid phase

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http://dx.doi.org/10.1016/j.ijplas.2015.02.001
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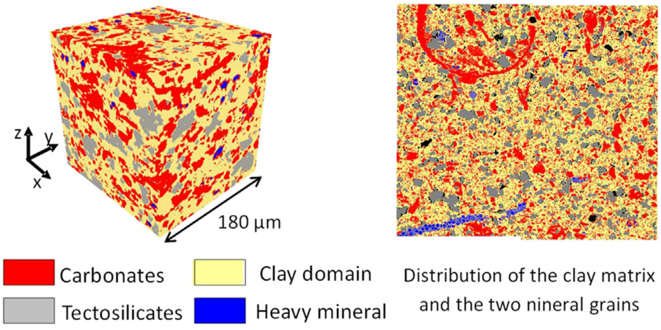

Fig. 1. Microstructure of the COX argillite at the mesoscopic scale (Robinet, 2008).

(clay particles) and inter-particular pores (Robinet, 2008). The average porosity is about 15% and the pore size varies between 20 nm and 50 nm. Due to the very long life of radioactive waste disposal, it is crucial to investigate long term thermo-hydromechanical behaviors of argillites. For this purpose, laboratory creep tests associated with microstructural analysis have been performed under different degrees of saturation (Chanchole, 2004). Among many factors influencing the time-dependent behaviors of argillites, the following two mechanisms play an essential role. The first one is related to the viscoplastic flow of clay matrix and the second one concerns the time-dependent propagation of microcracks in clay matrix (Abou-Chakra et al., 2009; Bornert et al., 2010). Indeed, various microscopic observations have revealed the existence of different propagation modes of microcracks inside the Cox argillites both under mechanical loading and moisture variation (Robinet, 2008; Bornert, 2010; Yang et al., 2012). On the other hand, many experimental studies have shown that microcracks can propagate slowly in time in a number of rocks and concrete due to complex physical and chemical phenomena such as stress corrosion, pressure solution and material dissolution etc. (Anderson and Grew, 1977; Henry et al., 1977; Waza et al., 1980; Atkinson, 1984; Nara and Kaneko, 2005, 2006; Chau and Shao, 2006). As the time-dependent crack propagation occurs even the applied loads are under the criterion for instantaneous propagation, it is usually qualified as a subcritical growth of microcracks which is responsible of macroscopic creep deformation. Based on experimental data, different kinds of macroscopic constitutive models have been proposed for the description of mechanical behavior in the clayey rocks (Shao et al., 2006a,b; Hoxha et al., 2007; Jia et al., 2010, just to mention a few). On the other hand, different constitutive models have been formulated for modeling of damage and plastic damage coupling in brittle metal or composite materials (Chaboche, 1981; Lubarda and Krajcinovic, 1995; Gambarotta, 2004; Brunig and Ricci, 2005; Khan and Liu, 2012; Balieu et al., 2013) as well as for quasi-brittle geomaterials such as rocks and concrete (Ju, 1989; Halm and Dragon, 1996; Hayakawa and Murakami, 1997; Voyiadjis et al., 2008; Comi and Perego, 2010; Shojaei et al., 2014). However, most models are devoted to time-independent behaviors of materials. Time-dependent strains are classically described by viscoplastic models. In some models, the damage evolution is coupled with viscoelastic and viscoplastic deformation (Rashid et al., 2012; Voyiadjis et al., 2004, 2012; Zhu and Sun, 2013). Some authors developed constitutive models taking into account the evolution of rock microstructure such as microcrack and bedding planes as the physical origin of creep deformation (Shao et al., 2003; Pietruszczak et al., 2004; Shao et al., 2006a,b; Zhou et al., 2008). Using nonlinear homogenization techniques, some micromechanical models have been developed for modeling of both plastic and viscoplastic behavior of clayey rocks (Abou-Chakra Guery et al., 2008, 2009). These models considered the viscoplastic flow of the clay matrix is the physical mechanisms of time-dependent behavior of clayey rocks. Recently, Huang and Shao (2013) have proposed a micro-macro model for modeling the creep deformation of the Cox argillites by considering the sub-critical propagation of microcracks in the clay matrix. However, their model was limited to the isotropic distribution of microcracks. Experimental investigations have clearly revealed an anisotropic distribution of microcracks which initiate and propagate in the clay matrix of Cox argillites (Bornert et al., 2010). In the present work, we propose an extension of this previous work to the description of subcritical propagation of anisotropic microcracks in the clay matrix. A two-step homogenization procedure will be used and its basic principle is shown in Fig. 2. At the first step, the effective elastic behavior of the anisotropic cracked clay matrix is determined

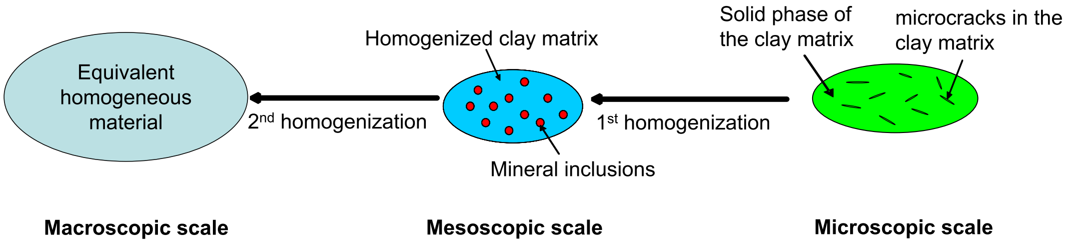

Fig. 2. Illustration of two-step nonlinear homogenization procedure.