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Examination of effective stress in clay rock

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ABSTRACT

This paper examines the effective stress in indurated clay rock theoretically and experimentally. A stress concept is derived from the analysis of the microstructure and of the pore water in the highly-indurated Callovo-Oxfordian and Opalinus clay rocks, and subsequently validated by various experiments performed on these claystones. The concept suggests that the interparticle or effective stress in a dense clay–water system is transferred through both the adsorbed interparticle pore water in narrow pores and the solid–solid contact between non-clay mineral grains. The experiments show that the adsorbed pore water in the claystones is capable of bearing deviatoric effective stresses up to the failure strength. The applied stresses are for the most part or even totally transferred by the bound pore water, i.e. the swelling pressure in the interparticle bound pore water is almost equivalent to the effective stress. This stress concept provides a reasonable view to the nature of the effective stress in argillaceous rock and forms the fundamental basis for studies of the hydro-mechanical properties and processes in clay formations.

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1. Introduction

Up to now, argillaceous rocks and compacted clays are commonly treated as a conventional porous medium, in which pore water is assumed to be freely migrating and physicochemical interactions of water with clay minerals are not explicitly taken into account. However, in indurated clay rocks, a considerable fraction of pore water is adsorbed on the internal and external surfaces of clay particles due to physicochemical interactions, and thus stress between clay particles must be transferred through the adsorbed pore water rather than directly via solid–solid grain contacts. Therefore, the important question arises whether the conventional views to the nature of effective stress are applicable to argillaceous rocks and compact clays. The conventional Terzaghi's effective stress defined as the interparticle stress due to direct solid–solid contacts between particles has been more theoretically examined for clay soils such as compacted bentonite, for instance by Mitchell (1976), Horseman et al. (1996), Rodwell et al. (1999), Sridharan (2001), and Yong et al. (2012). It is recognized that the effective

stress in compacted water-saturated clays is partly or even fully transferred by the adsorbed pore water between clay particles. For argillaceous rocks with less expansive clay minerals but more non-clay mineral components, however, the definition of effective stress is still unclear. Recently, our laboratory experiments have provided strong evidence for the significant role of bound pore water as a load-bearing element in indurated rocks (Zhang et al., 2010a, b, 2013). This paper investigates this fundamental issue theoretically and experimentally in order to highlight the important role of the bound pore water in a dense clay–water system, to improve the understanding of such a system and to increase confidence in models for strongly coupled hydro-mechanical processes in argillaceous formations that host radioactive waste repositories and other engineering constructions. It begins with a brief overview of the typical microstructures of the highly-indurated Callovo-Oxfordian (COX) and Opalinus (OPA) clay rocks, both being investigated as potential host rocks for repositories. On the basis of the microstructure, a stress concept will be derived for clay rock and then validated by laboratory experiments under various conditions.

2. Microstructure and pore water

The current state of an argillaceous formation results from its specific geological history over hundreds of millions of years,

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beginning with deposition and aggregation of fine-grained particles in sea water, followed by sedimentation and consolidation with a concurrent expelling of pore water, development of diagenetic bonds between mineral particles, and eventually erosion and uplift. The typical microstructure and the state of pore water in the COX argillite at Bure in France (ANDRA, 2005) and the OPA clay at Mont Terri in Switzerland (Mazurek et al., 2008; Bock et al., 2010) are illustrated schematically in Fig. 1. Both clay rocks have been over-consolidated to low porosities of 14%–18%. The COX argillite contains 25%–55% clay minerals, 20%–38% carbonates and 20%–30% quartz, while the OPA clay has a higher clay content (58%–76%), less carbonate (6%–24%) and quartz (5%–28%). Note that both clay rocks do not contain significant quantities of expansive clay minerals such as smectite: 13%–23% in the COX argillite (Tournassat et al., 2007) and 5%–20% in the OPA clay (Pearson et al., 2003).

The clay rocks have a clayey matrix embedding other mineral particles (quartz, calcite, and others). The clayey matrix consists of clay particles with strongly adsorbed interlayer water within the sheet structures and with strongly to weakly adsorbed water at the external surfaces. Large pores are filled with water that can freely migrate. The pore sizes in clay rocks mainly range from nano-scale (<2 nm) in between the parallel platelets of the clay particles to micro- and meso-scale (2–50 nm) between solid particles. The fraction of the pores smaller than 20 nm is about 60% in the COX claystone, while approximately 75% of the pores in the OPA claystone have a diameter in the range of 1–25 nm. The fraction of macro-pores (>50 nm) amounts to less than 10% for both the claystones. The thickness of the adsorbed water-film between clay particles is the most important factor governing the state and properties of the clay rock. For porosities of 12%–21% and specific surfaces of 20–160 m²/g, an average water-film thickness of 0.6–10 nm has been calculated (Rodwell et al., 1999). There is experimental evidence that water in micro-pores smaller than 7–8 nm is bound to the surface of the clay particles (Horseman et al., 1996). Comparison with the calculated water-film thicknesses indicates that the pore water in the COX and OPA claystones with porosities of 14%–18% is predominantly bound by these surface forces.

3. Establishment of a stress concept

Based on the knowledge of the microstructure and pore water state in the claystones, a conceptual stress model will be proposed

subsequently. Consider a representative volume of a saturated clay rock that is subject to compressive boundary stresses (σ_v/σ_h = vertical/horizontal stress) and immersed in an aqueous solution at pressure p_w , as schematically illustrated in Fig. 2. The external liquid is assumed to be chemically in equilibrium with the sample. The liquid pressure is transferred to the porous clay–water system and is equivalent to the pressure in large pores occupied by free bulk water. Clay particles including interlayer water are taken as microstructural units since the water molecules in the interlayer are strongly adsorbed within the sheet structures and immobile under usually encountered pressure gradients. The solid clay particles are connected through the double-layer. Under external mechanical compression, the particles are squeezed together so that the bound water-films can touch and be compressed together, resulting in a repulsive force between them. The contacts of a clay particle with an accessory mineral (carbonate, quartz and others) or of two accessory minerals can be considered to be a solid–solid contact.

Since the stress conditions at contact areas, rather than within particles, are of primary concern in a stress analysis of the porous clay–water system, a wavy surface that passes through contact areas between particles is of interest (Mitchell, 1976). Any wavy plane A–A can be selected in the clay sample, passing partly

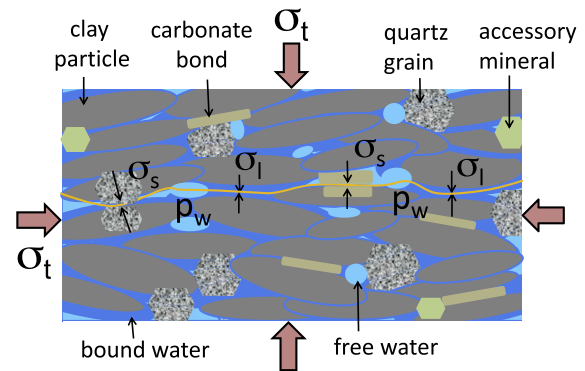


Fig. 2. Stress state in a representative element of a saturated clay mass. σ_s = pressure at solid–solid contacts, σ_l = pressure in interparticle bound pore water, p_w = pressure in free pore water.

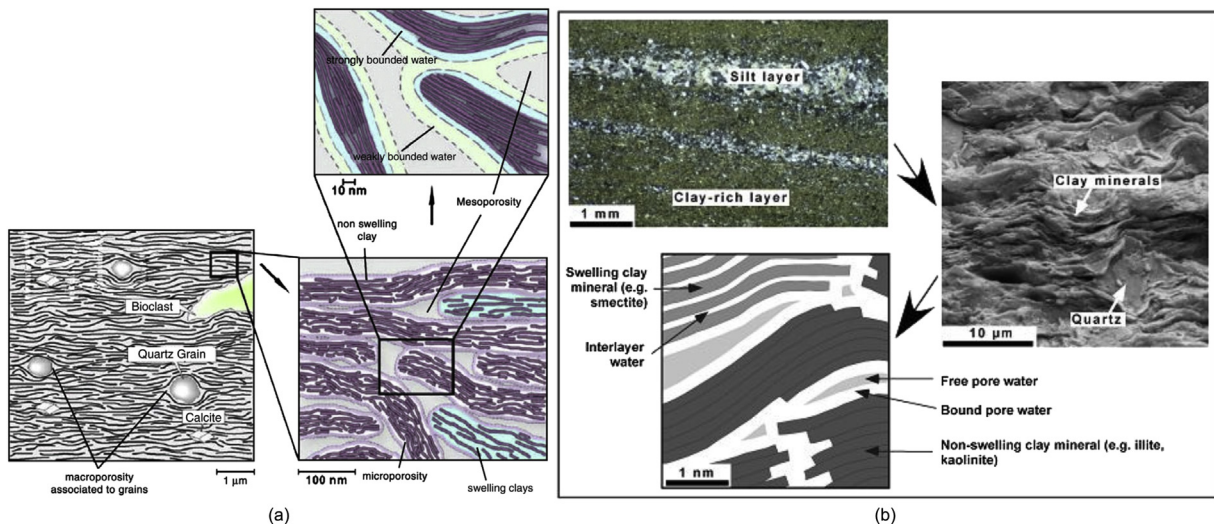


Fig. 1. Schematic diagrams of microstructures of (a) the COX argillite after ANDRA (2005) and (b) the OPA clay after Mazurek et al. (2008) and Bock et al. (2010).

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