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Anisotropy of seismic and mechanical properties of Opalinus clay during triaxial deformation in a multi-anvil apparatus

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Abstract

It is generally accepted that the dilatancy concept offers a reliable basis for the assessment of underground buildings in various host rock formations, e.g., a repository for radioactive waste. Stress conditions are predictable where creep failure and increasing permeability will inevitably develop. However, in argillaceous rocks an experimental detection of microcrack opening by volumetric strain measurements fails because the damage induced volume increase is overlapped by the dominating bedding plane compaction, also during deviatoric loading. To solve remaining uncertainties regarding the stress dependent onset of dilatant deformation in clay rocks it is inalienable to investigate the stress and deformation induced variations of various independently measured physical parameters, e.g., volumetric strain resp. porosity, p- and s-wave velocities, permeability. The aim of our spatial velocity measurements in a multi-anvil apparatus is not only to quantify the seismic anisotropy of the Opalinus clay but also to identify the onset of dilatancy and to monitor its evolution at various states of stresses. We found that the crack sensitive p- and s-velocities is a powerful tool for the determination of the so-called dilatancy boundary. Differences in the sensitivity of V_p and V_s, resp. anisotropy effects are closely related to the addressed physical process of crack opening depending on stress field orientation and bedding plane orientation. In summary, our results lead to a new and comprehensive synoptic view of the stress and deformation induced changes of rock properties in argillaceous rocks, which impressively confirms the general concept of dilatancy.

Keywords: Opalinus clay; Mechanical strength; Permeability; Dilatancy; Anisotropy; Microstructure; EDZ; Radioactive waste

1. Introduction

Mining of underground galleries and cavities generally results in development of an excavation disturbed/damaged zone (EDZ), which affects the efficiency of geological barrier systems at least while operation and closing phases. A prognosis of the EDZ initiated by mining activities is only possible with evolvement of suitable material laws corresponding to respective host rock that allow a numerical simulation of the complex hydro-mechanical behaviour of the surrounding host rocks associated with the contrasting processes of brittle deformation and healing while operating the repository. Dilatant deformation resp. an increase of porosity as a consequence of decompaction leads concomitantly to an increase of permeability, i.e. loss of barrier integrity of the host rocks.

In the lab the amount of brittle deformation of rocks is generally quantified by the parameter dilatancy, i.e. the development of micro-fractures, which depends on the state of stress (stress field geometry and deviator). The determination of the stress dependent onset of dilatancy, described by the dilatancy boundary criterion, is, therefore, of predominant importance for an appraisal of barrier properties of solid rocks (e.g., Cristescu and Hunsche, 1998; Hunsche and Schulze, 2003).

However, in contrast to other rocks (e.g., salt or granite) argillaceous rocks are inherently anisotropic (more pronounced for indurated clays than for plastic clay); which

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complicates the parameter determination. In particular, the existing bedding provides extreme differences in directional properties (anisotropy) in strength, permeability, electrical conductivity, and seismic velocity (e.g., Zhang and Rothfuchs, 2004; Valés et al., 2004). Bedding plane anisotropy can be achieved by both macroscopic and microscopic layering of clay minerals or lithological different rock units (sand-shale sequences). Thus, it can be anticipated that an understanding of these complex interacting processes between lithological and physical properties has to be based on well controlled laboratory tests.

As a tentative basis for a successful experimental attempt investigating dilatant deformation processes Fig. 1 compiles property changes of a hypothetical rock during strength testing ($\dot{\varepsilon}$ = constant) in a synoptic diagram:

Stage I appears essentially under low confining pressures and is attributed to the closing of pre-existing cracks or dilated grain boundaries. The initial elastic loading is followed by anelastic deformation whereby it remains unclear if at that stress level damage already starts. Exceeding a certain differential stress causes the transition from non-dilatant to dilatant behaviour. Progressive onset of dilatancy (between domains I and II in Fig. 1) is associated with acoustic emission, increase of volumetric strain and permeability, and decrease of ultrasonic wave velocities. For example, Horsemann et al. (2003) suggested the deviation of the measured volumetric strain from the linear compaction for the determination of the dilatancy strength of Callovo-Oxfordian-claystone. However, onset of dilatancy is not simply to identify because as came out by extensive laboratory investigations on salt rocks relevant sensitiveness for the various parameters of fracture development has to be considered (e.g., Popp et al., 2001; Schulze and Popp, 2002).

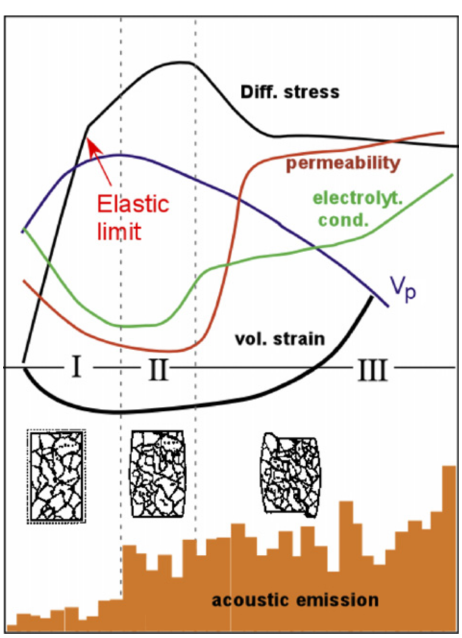

Fig. 1. Scheme illustrating changes of physical properties during deformation. Volume change, acoustic emission, permeability, and ultrasonic wave velocity are used to monitor dilatancy (modified after Schulze et al., 2001).

In consequence of both, the inherent anisotropy of clay rocks and uncertainties if only one parameter is measured, we performed non-hydrostatic loading tests with simultaneous transmission measurements of V_p and V_s, in addition to shear wave splitting estimations, in three perpendicular directions on Opalinus Clay sample cubes. The aim of these tests is not only to quantify the seismic anisotropy due to the in-situ state of the microstructure but also to identify the onset of dilatancy and to monitor its evolution at various states of stresses.

2. Material description and Rock fabric

The material was recovered from two bore holes at the Mont Terri site in Switzerland: BLT 1 and BLT 2, which were drilled in January 2001 during the drilling campaign 6 of the Mont Terri project. The mouths of the hole are located in the SHGN niche at position SG 905.54 (BLT-1: 10.10 m length) 0.97 m above bottom resp. at position SG 905.60 (BLT-2: 14.0 m length) 0.65 m above bottom. The holes with a diameter of 131 mm were horizontally drilled with a double core barrel in WSW direction (236°).

The investigated material was cored with a 101 mm diameter tungsten carbide bit and cooled with dried air. The samples were cut in the shaly facies at a distance of 2.90–8.40 m from the gallery to provide mechanical data of non disturbed media. All samples were sealed in aluminium coated foil.

The core samples were carefully machined with a fine band saw by the BGR staff into 11 cubic specimens of 43 mm edge length. The bulk density of the specimens was observed to be 2438 ± 10 kg/m with a porosity of $\sim$15% and a water content of $\sim$6.0%. The general mineralogy of the rock is summarized in Table 1.

The prepared samples showed thin bedded dark grey clay minerals with a typical anisotropic texture of clay particles parallel the bedding surface, which was created during sedimentation and tectonic induced compaction processes as schematically shown in Fig. 2. The strong shape orientation of the various platy clay minerals was characterized by X-ray diffraction texture measurements performed on sample cylinders with 20 mm in diameter which were cored perpendicular to the macroscopically visible foliation (Analyst: G. Braun, University of Kiel). Characteristic lattice planes (h k l) of various clay minerals were measured (0 0 x) with a diffraction goniometer in reflection mode using Cu(kα) and necessary intensity corrections were made (e.g., Braun, 1994). The pole figures are given in equal area projection (upper hemisphere) corresponding to the reference system.

Fig. 2b shows the pole figures for (0 0 2) of chlorite and a mica mineral of the virgin material. They indicate develop-