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An experimental and numerical evaluation of continuous fracture permeability measurements during effective pressure cycles

Harald Milsch [a,*], Hannes Hofmann [a,b], Guido Blöcher [a]

[a] GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
[b] Energy and Sustainability Research Institute, University of Groningen, Nijenborgh 4, 9747 AG Groningen, The Netherlands

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1. Introduction

Fluid transport within the Earth's crust is controlled by planar void space like crack networks and fractures unless flow through the rock matrix becomes important, e.g., in porous sedimentary systems. An understanding of the former rock structural elements and their hydro-mechanical properties therefore is of importance for a variety of both geoscientific and geotechnical themes like diagenesis, ore formation, metamorphic reactions, crustal deformation, and earthquake mechanics, as well as CO_2-sequestration, enhanced oil recovery, and nuclear waste storage, to name a few. Particularly, the efficiency of geothermal energy provision from deep geological formations predominantly relies on the hydraulic performance of cracks and fractures either preexisting or artificially created within a reservoir by hydraulic or thermal stimulation treatments. Central to all of these topics is the rock-type and scale dependent evolution of fracture permeability as a function of stress, temperature, time, and fluid chemistry. Consequently, various aspects of fracture hydro-mechanics have received attention in numerous theoretical, experimental, and field studies. Most recent reviews on the subject are provided in [1,2].

Of fundamental interest in this context is finding the appropriate fluid transport equation with respect to fracture morphology e.g.,[3–5], understanding the relationship between aperture of single rough fractures and normal stress e.g.,[6–8], and identifying processes that yield time dependence of fracture permeability e.g.,[9]. A rather limited number of experimental studies address the evolution of fracture permeability in selected rock types with time and feedbacks from stress and/or reactive chemical processes: on granite [2,10–12], on limestone [13,14], and on novaculite [15].

Here, we present results of fracture permeability measurements conducted on one carbonate rock sample during slow effective pressure cycles to distinguish and quantify different modes of brittle, elastic and time dependent mechanical response. However, the paper's prime purpose is to demonstrate that continuous fracture permeability measurements conducted during pressure cycling are feasible and meaningful when based on the steady state method. For this to evaluate, a numerical model was set up to calculate the dissipation time of induced pore pressure disturbances as a function of fracture aperture. Such disturbances, nominally, would yield a departure from steady state conditions and consequently errors in so derived permeability. Ultimately, the numerical simulation will constrain the minimum fracture aperture for which continuous measurements provide reasonable means for fracture permeability monitoring under dynamic loading conditions.

2. Sample material and experimental procedures

As sample material one type of Malm carbonate, Treuchtlinger

* Corresponding author.
E-mail address: milsch@gfz-potsdam.de (H. Milsch).

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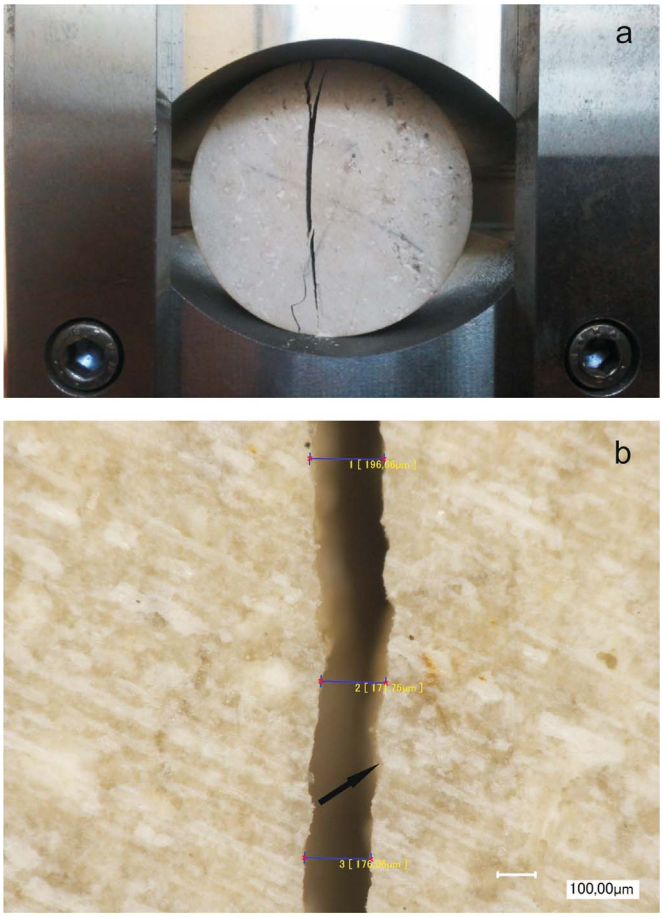

Fig. 1. Artificially fractured sample TM-1. (a) Sample after fracturing in Brazilian test setup. (b) Optical micrograph of the single fracture with visible offset (arrow) of the two fracture walls.

Marmor (TM), was selected from an outcrop in the German Molasse Basin[16]. This rock is a Lower Malm, Middle Kimmeridgium (Delta) thick-bedded limestone with sponges. It consists predominantly of calcite and is only weakly dolomitized.

One specimen was prepared in cylindrical shape with 5 cm in diameter and 10 cm in length and was then split along the principal axis to create one defined artificial tensile fracture (Fig. 1a and b). Splitting was performed in a Brazilian test setup using an MTS uniaxial rock deformation apparatus. As evident from Fig. 1b and indicated by the arrow the two fracture walls experienced a small shear offset of approximately 80 µm in the direction perpendicular to the principal sample axis. During splitting the sample was maintained in a heat shrink tubing which was not removed but kept for the subsequent permeability measurements. In the following the sample will be denoted TM-1.

Before fracturing, the intact sample porosity ($\varphi = 5\%$) and permeability ($k = 1 \times 10^{-18}$ m^2) were determined. Porosity was measured by helium pycnometry and additionally by comparing dry and wet sample mass. Wet sample mass was determined after saturating the specimen in vacuum. Distilled water was used as the pore fluid in all experiments. Permeability was measured in a Hoek-cell[17] with one high precision syringe Pump (Quizix Q6000) upstream and the downstream side of the sample open towards the atmosphere. The use of this type of cell permitted to determine the poroelastic response of sample permeability up to confining pressures of 20 MPa. Measurements were conducted at laboratory temperature approximating 20 °C.

The subsequent experiment on the fractured sample was performed in an MTS conventional triaxial deformation apparatus under hydrostatic loading conditions with oil used as the confining pressure medium. Permeability was measured at 30 ± 1 °C to avoid disturbances by laboratory temperature variations. A background pore pressure of 0.1 MPa was applied and confining pressure was cycled twice between 2 and 40 MPa, i.e. two times up and down, at a rate of approximately 0.5 MPa/h. During the second cycle effective pressure was maintained constant at 40 MPa for approximately 10 h to investigate potential time dependent effects in mechanical response of the fractured sample. One full cycle including the time required for permeability measurements therefore took approximately one week. In the following, the term "effective pressure" relates to the difference between confining and pore pressures as defined by Terzaghi [18].

Permeability of the fractured sample was measured either step-wise (during the first pressure cycle) at defined effective pressure levels or continuously (during the second pressure cycle), in both cases with one upstream pump maintained in constant flow mode and one downstream pump operated in constant pressure mode at 0.1 MPa. For step-wise measurements a flow rate of 5 ml/min was applied limiting the maximum pore pressure upstream to 1 MPa at minimum fracture aperture. Continuous measurements were conducted by imposing the same, constant flow rate throughout confining pressure ramping and recording the differential pore pressure as it developed with time. In both cases, permeability was then calculated by applying Darcy's Law directly e.g.,[19]. In the following, results for the fractured sample will be reported as either sample or fracture permeability with reference to the sample's and the fracture's cross-sectional areas, respectively. This is an important point to distinguish as sample permeability is precisely derived from the measurement itself. In contrast, fracture permeability is a secondary quantity that relies on the assumed geometry of the fracture, e.g. parallel plates, as outlined in Section 4.2.

3. Numerical model setup

To investigate the applicability of continuous permeability measurements based on the steady state method a three dimensional finite element (FE) model of the experiment was set up using the multiphysics simulator Comsol.[c] The modeled rock specimen consists of two different domains. A two dimensional plane with a given aperture representing the fracture (5 cm wide and 10 cm long) was embedded in a cylindrical 3D mesh (5 cm in diameter and 10 cm in length) representing the rock matrix. In addition to the rock specimen, the capillary in the lower end cap of the triaxial cell was explicitly modeled by a squared cross section with 1 mm edge length. The model consists of 9752 tetrahedral elements with edge lengths between 1 mm and 1.2 cm.

Fluid flow was modeled with Darcy's law in both the matrix and the capillary and the "cubic law" [e.g.,[3]] in the fracture assuming smooth laminar flow between two parallel plates. Additionally, storage was considered for all three model domains, i.e., matrix, capillary, and fracture.

The model parameters of the three domains are given in Table 1. The injected fluid was pure water at 30 °C with a dynamic viscosity of 0.796 mPa s, a density of 996.66 kg/m^3 and a compressibility, i.e. storage, of 4.6×10^{-10} 1/Pa. While all other parameters were kept constant, models with different fracture apertures between 1×10^{-8} m and 5×10^{-5} m were set up.

As starting condition, a homogeneous pore pressure of 0.1 MPa was set within all three domains of the model. Afterwards, this pressure was maintained at the top of the sample (downstream) as

[c] https://www.comsol.com.