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Measurement of spatial distribution of total and accessible porosity in sedimentary rocks using isotopic radiation transmission: Device design and testing

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ABSTRACT

An isotopic radiation transmission technique for quantifying the spatial distribution of porosity in sedimentary rocks is presented. A device was designed and constructed to examine rock samples of volumes sufficiently large for studying solute migration in rocks, so that a one-millimeter spatial resolution is attained with measurement acquisition time of one point per second. The paper demonstrates how the device was optimized for these specifications, while abiding by the restrictions implicit in the utilization of the exponential law of radiation attenuation to quantify physical parameters. Total porosity was obtained from measurements of radiation attenuation in dry samples, while solute-accessible porosity was determined from measurements with samples saturated with either KNO_3 or KI solutions. Results are presented for three different rock types to demonstrate the capabilities and limitations of the technique.

1. Introduction

In the disposal of nuclear and chemical waste in stable geological rock formations, the long term integrity of a repository depends on the ability to prevent the outward migration of soluble components of the waste, and the inward migration of reactive solutes that can threaten the chemical stability of the waste (Gascoyne et al., 2002). For many waste disposal facilities, sites with low-permeability bedrock materials (e.g. shale, limestone, granite) are sought in order to isolate the waste, and prevent transport of contaminants away from the disposal facility. Rocks contain an intricate network of connected pores and microfractures through which solutes may migrate (Jakob, 2004). Understanding and modeling these transport processes requires measurement of, not only the overall bulk porosity, but also the spatial distribution of porosity within the rocks. The pores of importance are those that are accessible by transported solutes, but a measurement of total (accessible and inaccessible) porosity will also be useful in assessing the suitability of a certain rock formation for use as a waste repository.

Recent effort in characterizing sedimentary rocks has taken advantage of available imaging technology, which enables the non-destructive measurement of porosity. Tidwell and Glass (1994) and Altman et al. (2004) utilized X-ray absorption imaging (radiography), Cavé et al. (2008) employed digital micro-radiography (using a micro-CT machine), Nakashima (2000) utilized computed tomography (CT), while Marica et al. (2005) applied magnetic resonance imaging for spatially resolved porosity measurements. These are powerful measurement techniques, but have their own limitations. Magnetic resonance imaging can be used to determine the distribution of connected pores, by measuring the concentration of solutes containing certain nuclei susceptible to magnetic resonance (e.g. ^{1}H, ^{3}H, ^{13}C). These are small atoms that do not resemble the typically larger ions and molecules associated with radioactive waste. X-rays used in either radiography or tomography suffer from the fact that their indications are not directly related to porosity or solute concentration, due to the multichromatic nature of X-ray photons and the beam hardening effect associated with thick and/or dense objects, even after filtering low-energy photons. Nevertheless, a well-filtered high-voltage X-ray machine may be used to produce

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a quasi-monochromatic beam, which along with readily available high-resolution array detectors, can produce a fast response, but at increased cost and complexity. Available commercial CT systems are designed for large test objects (encountered in medical and industrial systems), while micro-tomography systems are limited to small-size objects.

In conducting experiments involving solute transport in porous media, it is important to consider the sample size with respect to the size of the representative elementary volume (Bear, 1972). A test sample volume of 85 mm × 45 mm × 25 mm is considered appropriate for many common sedimentary rock types. This size of test object is too large for a micro-CT system and too small for a commercial CT machine. Also, the beam hardening effect at this thickness for this type of material is quite considerable, making it difficult to adequately quantify and interpret the measurement results using X-ray sources. For these reasons, we endeavored to develop a special-purpose radioisotope-based device.

This paper reports the development of a technique that employs the radiation transmission modality with a monoenergetic radioisotopic source. The technique is specially tailored to the measurement of rock samples of the size commonly employed in geological studies of solute transport in rock. The test cell used in such studies is described below, followed by a presentation of the design aspects of the measurement technique and the methods for relating radiation counts to the porosity parameters of interest. Results are then given to demonstrate the capabilities and limitations of this technique.

2. Test cell

Rectangular 85 mm × 45 mm × 25 mm rock samples were utilized in this work. Each sample was fitted inside a test cell, consisting of bars of aluminum cut to fit around the edges of the rock sample. Two reservoirs were milled inside each test cell, one at the top and another at the bottom, which allowed the saturation of the sample with the desired solute. A schematic diagram of the test cell is shown in Fig. 1.

This work focused on measuring the distribution of pores accessible by both a weakly radiation-absorbing solute, potassium nitrate ($K^+ NO_3^-$), and a strong radiation-absorbing solute, potassium iodide ($K^+ I^-$). The I^- ion is close in nature to solutes expected in nuclear waste. Both these solutes are geochemically conservative, i.e. do not chemically interact with rock formations, and as such do not alter the characteristics of examined samples, allowing the determination of the rock's natural porosity distribution. Potassium iodide has a high gamma-ray absorption coefficient, which makes it a good contrast material in radiation measurements. Therefore, in addition to acquiring radiation transmission measurements for a dry sample to obtain the total porosity, ϕ_t, measurements were also taken with samples saturated with KNO_3, to obtain the porosity distribution for KNO_3 accessible pores, ϕ_{KNO_3}, and with samples saturated with KI to determine, ϕ_{KI}, the porosity accessible by KI.

The bulk porosity of connected pores (water-loss porosity) of rocks employed in this work was measured using a gravimetric analysis based on water imbibition (Emerson, 1990). The mineralogical characteristics of very fine-grained rock samples were also studied using a scanning electron microscope (JEOL JSM6400 SEM).

3. Design of radiation-transmission device

The well-known exponential attenuation relationship for an incident radiation of intensity I_0 through a material of attenuation coefficient μ and thickness d predicts a transmitted intensity I in accordance to

$$I = I_0 \exp(-\mu d) \tag{1}$$

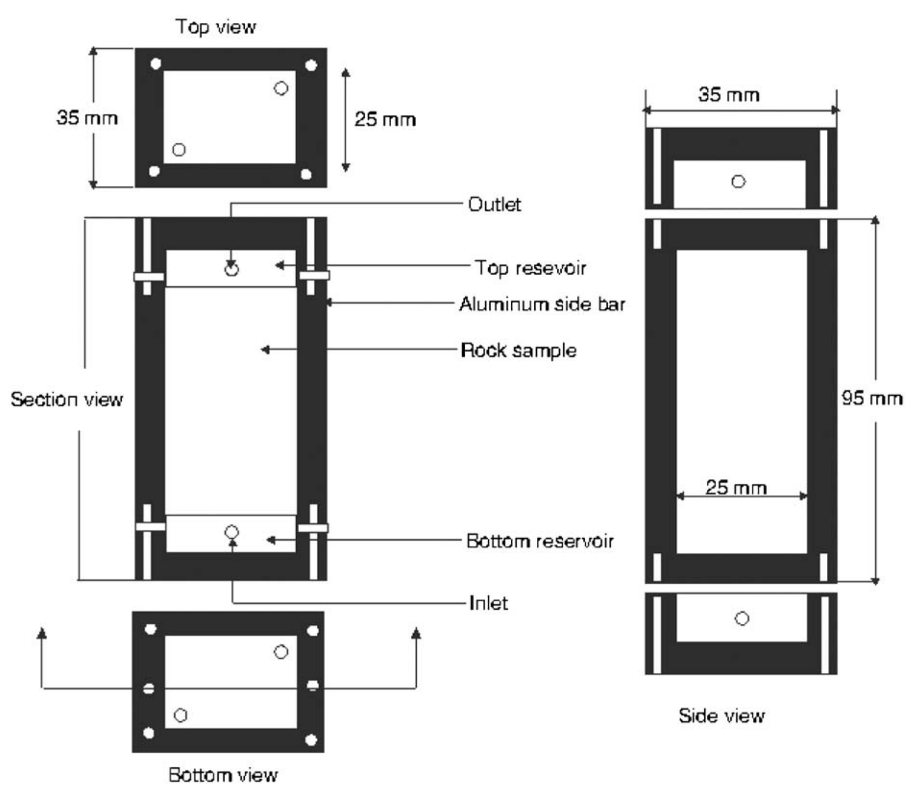

Fig. 1. A schematic of the test cell: cross-section and side views: radiation passes in a direction normal to page.