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3D X-Ray CT and Diffusion Measurements to Assess Tortuosity and Constrictivity in a Sedimentary Rock

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1. Introduction

The understanding of the role of pore structure/dimension/geometry and connectivity on migration properties of radionuclides in natural rocks is one of key factors of performance assessment in deep geological disposal systems of high level radioactive waste. For the assessment, there is a need to model or predict the effect of the porosity on the migration of the radionuclides. The effective diffusion coefficient, D_e, defined by $D_e = \varphi\delta/\tau^2 \times D_w$ (φ: diffusion-accessible porosity, δ: constrictivity, τ: tortuosity, D_w: diffusion coefficient of ions in free water) [1]. The diffusion-accessible porosity can be experimentally obtained from the steady state breakthrough behaviour of non-sorbing radionuclides. Tortuosity and constrictivity are used as adjustable parameters in conventional models of radionuclides migration in porous media. The direct measurement of those factors in relation to the real pore structure has not been performed so far. The macro-pores will be main diffusion path which directly affects accessibility of radionuclides and will contribute the diffusivity largely if the macro-pores connect throughout the rock. In the present study, direct observation of macro-pore geometry, their distribution and their connectivity in sedimentary rock sampled from Horonobe underground research laboratory (URL) site was performed by means of nano-focus X-ray computer tomography (X-ray CT) to identify real tortuosity and constrictivity of the rock followed by prediction of D_e based on the measured pore characteristics.

2. Methods

An about 300 μm diameter and length specimen was prepared from a larger sedimentary rock sampled from 500 m in depth at Horonobe URL. The specimen was imaged at 270 nm voxel resolution by means of the nano-focus X-ray CT. The image was processed by using the software package Exfact Analysis for Porous/Particles (Nihon Visual Science, Inc.) to extract contour of pore geometry and percolating pores to assess medial axis [2] and connectivity of pores and to determine geometrical path tortuosity (defined as the ratio of length of a path to the apparent length of the rock sample) and radiuses of pore, r_p, and throat, r_t [3]. Constrictivity, δ, was determined from equation (1) [4] using the r_p and the r_t.

$$\delta = \frac{(\text{maximum} \times \text{minimum cross-section})^{1/2}}{\text{mean cross-section}} = \frac{(\pi r_p^2 \times \pi r_t^2)^{1/2}}{\frac{1}{2}(\pi r_p^2 + \pi r_t^2)} \qquad (1)$$

The effective diffusion coefficient of HTO, D_e, and the diffusion-accessible porosity, φ, were measured by through-diffusion experiments using the sedimentary rocks with 20 mm in diameter and 20 mm thicknesses for horizontal and vertical direction of the specimen to the ground.

Table 1 Accessible porosity, effective diffusion coefficient and the δ/τ^2 obtained from HTO diffusion experiments.

Direction to the ground	φ	D_e/m² s⁻¹	δ/τ^2
Vertical	0.19	8.80×10^{-11}	0.216
Horizontal	0.22	1.02×10^{-10}	0.217

3. Results and Discussion

The τ distributions of horizontal direction (X and Y) and vertical direction (Z) to the ground are displayed in Fig. 1. The average of τ distributions in the X, Y and Z directions were 2.94, 2.18 and 2.64, respectively. The average of τ in the X, Y and Z directions was estimated at 2.59. The average of the constrictivity was estimated at 0.58 using the r_p and r_t.

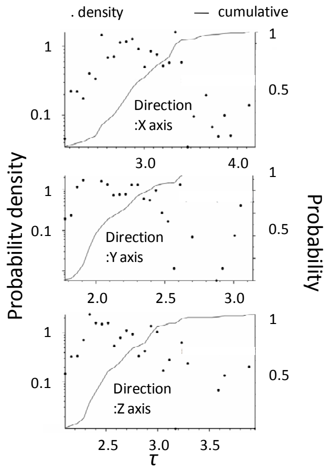

Fig. 1 The τ distributions of X, Y and Z directions.

Accessible porosity and effective diffusion coefficient of HTO form diffusion experiments and the δ/τ^2 calculated from the data were shown in Table 1. The value of δ/τ^2 at 0.081 derived from 3D X-ray CT image analysis is much smaller than the values obtained from diffusion experiments. It indicates that the δ can be neglected and the pore sizes of the sedimentary rock samples investigated here are much bigger than the HTO [5]. The value of $1/\tau^2$ at 0.15 derived from 3D X-ray CT image analysis is in reasonably good agreement with the values obtained from diffusion experiments. This consistency indicates that the geometrical structure of HTO diffusion path was similar to the one measured by X-ray CT.

4. Conclusion

The results of the direct measurement of the 3D pore structure by means of X-ray CT and the diffusion measurement indicate that the dominating parameters that control diffusion of HTO in the present system are not the δ but the φ and the τ.

References

[1] M. García-Gutiérrez, J. L. Cormenzana, T. Missana, M. Mingarro, Appl. Clay Sci. 26 (2004) 65–73.

[2] W. B. Lindquist, S. M. Lee, D. A. Coker, K. W. Jones, P. Spanne, J. Geophys. Res. 101B (1996) 8297-8310.

[3] H. Takahashi, Y. Seida, K, Miyahara, M. Yui, Interfaces Against Pollution 2008 Program & Abstracts, p. 259.

[4] J. A. Currie, Brit. J. Appl. Phys. 11 (1960) 318-324.

[5] T. B. Boving, P. Grathwohl, J. Contam. Hydrol., 53 (2001) 85-100.

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