First Petrophysical Data Compilation on the Effectiveness of an Extensive Hydraulic Barrier during Mine Water Rebound in the Ruhr District – the Upper Cretaceous Emscher Formation.

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Abstract

The assessment of the intrinsic permeability/hydraulic conductivity of potential cap rock formations is an essential risk management task associated with the mine water rebound in the Ruhr district area. Hydraulic barrier evaluation is necessary to test safeguards for mitigating potential threats of drinking water reservoir contamination during rebound. Petrophysical data obtained from core material of Emscher Formation were measured in order to assess its future mine water infiltration potential. The Coniacian to Middle Santonian Emscher Formation acts as a major aquitard in the region. The aim is to capture the heterogeneity of the rock formation including its anisotropic behaviour.

Keywords: Mine Water Rebound, Ruhr District, Hydraulic Conductivity, Cap Rock, Risk Management

Introduction

The extensive mine water rebound process in the former hard coal mining area of the Ruhr District covers an area of about 5000 km^2. Major hydrogeological changes in the area are anticipated during rebound, which makes the assessment of intrinsic permeability/ hydraulic conductivity of potential cap rock formations in the region an inevitable task in the context of risk management. For sustainable mine water management, consideration of hydraulic conductivity to assess fluid movements in the subsurface is essential. The increase in mine water levels and the associated reduction in mine water dewatering stations are the main components of the mine water concept. A gradual increase from an average pumping height of 900 to 600 meters makes it possible to reduce the number of mine water drainage sites from 13 to 6 and to free the Emscher river from mine water. The primary protection goal, the protection of drinking water resources, must be guaranteed by ensuring a permanent vertical distance of 150 meters to the mine water. For a comprehensive picture of the overburden's hydraulic behaviour a lithostratigraphic, petrological and petrophysical analysis of monitoring wells drilled by RAG AG were carried out. Petrophysical parameters of porosity, permeability and hydraulic conductivity were the major focus. Core plug samples from the Coniacian to Middle Santonian Emscher Formation ("Emscher Marl") and for internal quality control of the well conductive Bentheim sandstone were examined. Previous data assessment on the Emscher Formation exhibit only coarse hydraulic conductivity data of $k_f = 10^{-10}$ to 10^{-9} m/s on the matrix for modelling purposes (Coldewey and Wesche 2017). Such data will be verified by direct measurements using porosimetry and gas permeametry.

Methods

The Hg-porosimeter Autopore V9600 from Micromeritics was used to examine plugs with a length and a diameter of about 2.5 cm each (Figure 1). As a standard application, mercury (Hg) was used up to a pressure of 414 Mpa for the porosity measurements due to its low wettability and high surface tension. Hence, mercury does not wet most substances and will not penetrate into pores by capillary action. It needs to be forced into the pores applying pressure and in the experiments, the Washburn equation was used to relate pressure to pore diameter

Figure 1 Plug samples from the Emscher Marl and Bentheim Sandstone (image: Lisa Rose).

Table 1 Results of the Porosimetry examinations on plug samples from the Emscher formation (EM) and the Bentheim sandstone (BS).

sample	Entire pore volume	Medium pores diameter	Average pore diameter	Total density	Skeletal density	porosity
	m^{2}3?/g	µm	µm	g/mL	g/mL	%
EM h1	9,951	0,03475	0,02582	2,2900	2,6850	14,7094
EM h2	10,658	0,02954	0,02326	2,2740	2,6471	14,0959
EM h3	10,145	0,03322	0,02570	2,2735	2,6690	14,8192
EM v1	10,581	0,03544	0,02677	2,2369	2,6579	15,8393
EM v2	12,310	0,02800	0,02128	2,2497	2,6385	14,7360
EM v3	11,475	0,02646	0,02175	2,2858	2,6660	14,2636
BS v1	0,147	28,10055	3,19340	2,0061	2,6233	23,5259
BS v2	0,310	26,49321	1,35345	2,0846	2,6680	21,8660
BS h1	0,269	27,70771	1,64421	2,0318	2,6207	22,4717

and later on includdie density to intrusion volumes (mg/L). The helium gas pycnometer AccuPyc II 1345 from Micromeritics was used to determine the skeletal and total (true) density of the plug samples. The density data is measured as well during porosimetry for verification and quality control. The examined core samples of the Emscher Marl are from a basal section of the Pferdekamp 1 well from the depth 495.68 - 495.96 m. Plugs made of Bentheim sandstone, Gildehaus type, were drilled for benchmarking purposes of the instrument.

To produce the plug samples, suitable blocks of Bentheim Sandstone were selected and the approximately 30 cm long Emscher Marl core material was cut into multiple sections. These sections were positioned horizontally or vertically on a round plate and stabilized with plaster. Then the rock saw was used to cut pieces from above, which subsequently were cut to the correct length and each side of the plug was ground to a parallel plane.

Results

The results of the measurements are indicated in Table 1. The Emscher Marl has an average porosity of 14.7 %. Its average pore diameter is 0.03 µm. The Bentheim Sandstone, on the other hand, has an average porosity of 22.6 ± 0.6% and an average pore diameter of 27.43 ± 0.62 µm which fits well with data obtained from Hossain (2019) and Ma (2016) who measured mean porosities of 22.75 ± 0,25% and 24.0 ± 0,4% for similar Gildehaus type samples. Figure 2 illustrates the petrophysical differences of the two rocks. While the

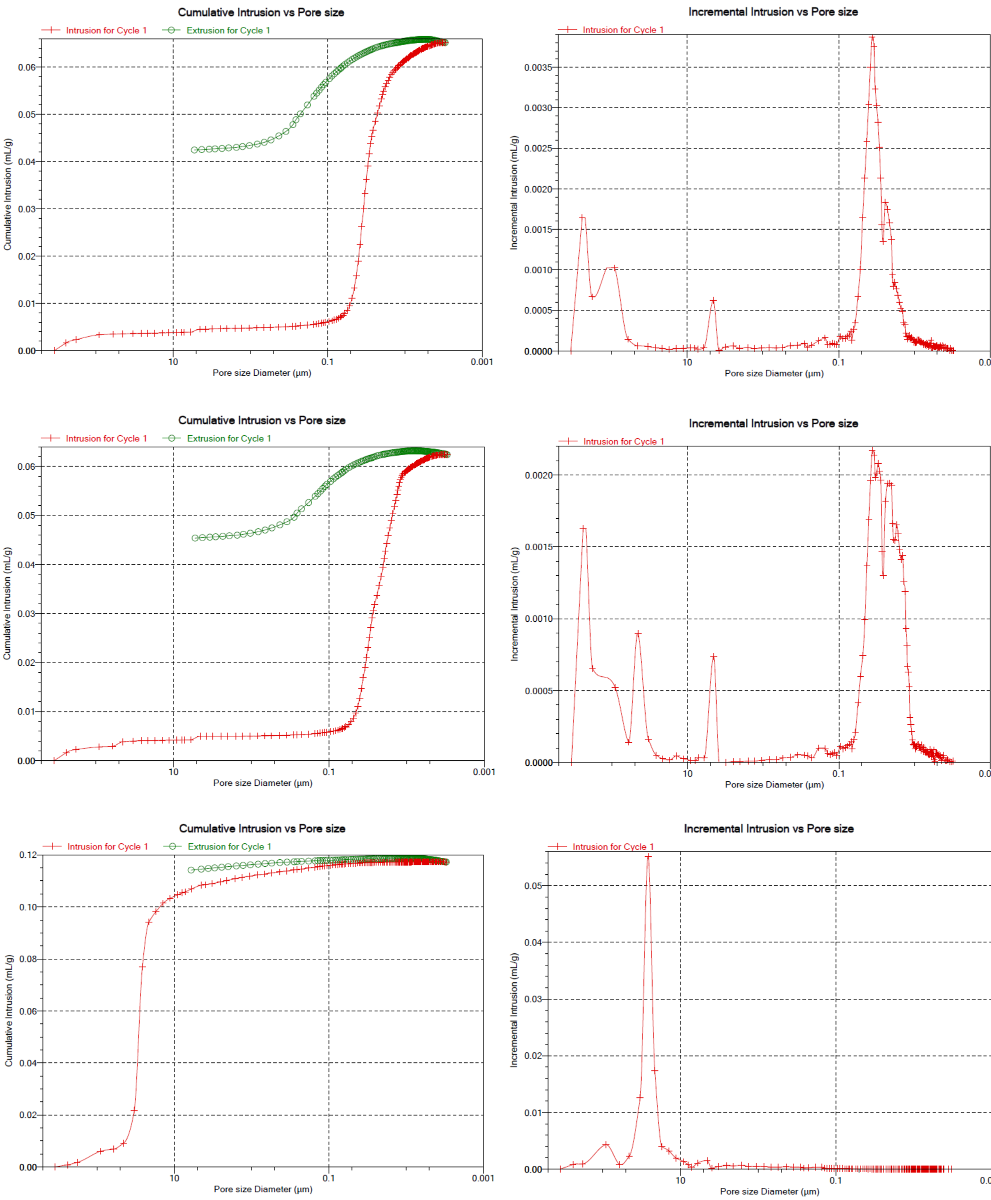

Figure 2 Mercury intrusion and extrusion curves on plug samples: EM H3 (top), EM V3 (center), BS V1 (below); Cumulative intrusion volume vs. pore size and intrusion volume-increment vs. pore size graphs were plotted for each sample.

porosity and the average pore diameter of the sandstone are similarly high, the values of the Emscher marl are far apart.

In mercury porosimetry, the sample is flushed under pressure in a penetrometer with mercury. Depending on the pressure applied, the mercury is forced into the pore spaces. It depends on the so called smallest *pore throat diameter* which pores are filled with the non wettable fluid. In addition to this important diameter, which can be used for permeability determination, pore geometries can also be derived from the pressure volume curves. In the tests, pressures up to 414 MPa or 60,000 psia were reached, which corresponds to the smallest pore diameter of about 0.006 µm or

60 Angström to be flushed. Pores of up to 360 µm in diameter form the upper limit of the possible measurable pore diameter. In Fig. 2, the graph of the volume increments vs. pore sizes show a pronounced bimodality in the range of 0.02-0.04 µm for the two Emscher Formation plugs. The horizontally drilled sample indicates a slightly stronger compaction and a dominance of the larger pore diameter. The vertically drilled sample is characterized by a 50:50 distribution of two pore volumes. The Bentheim Sandstone as a counterpart shows an unimodal pore size distribution with a sharp peak at approx. 25 µm, cylinder to equidistant pore geometries and very good permeability.

Conclusions

The average pore diameter of the Emscher Marl is very small at 0.03 µm. With an average of 14.7%, the Emscher Marl has a comparatively high matrix porosity compared to its pore diameters which is an important finding and can play a role in the petrophysics of the rock . In comparison, the Bentheim Sandstone has a high matrix porosity of 22.6% on average and very large pores with an average pore diameter of 27.43 µm which underpins is excellent reservoir rock properties acting as an excellent fluid conduit. Due to the low pore diameter, the Emscher Marl indicates very low permeability for fluid despite its high porosity, which might have implications for gas migration and storage compared to fluid movements. To infer permeability from the porosimetry data, Katz-Thompson method will be applied to infer the corresponding permeability values in the future.

Models are required to transfer the determined hydraulic properties to a larger scale, such as entire well sites, well clusters and entire rock formations. Since the measurable samples only represent a tiny fraction of the entire Emscher Marl formation, it is important to identify the hydraulically relevant structural elements first. As a next step, representative samples can be taken from the desired areas. Spatial arrangement and hydraulic conductivity are closely related and are both scale-dependent properties of rock masses. These properties are important to consider for the correct interpretation of the test results. Very low permeable rocks, such as the Emscher Marl, can be measured more accurately and faster on small scale plugs.

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