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THE STUDY OF GAS MIGRATION IN CRYSTALLINE ROCK USING INJECTION TESTS

ISPITIVANJE MIGRACIJE PLINA KROZ MAGMATSKU STIJENU PRIMJENOM INJEKCIJSKOG POKUSA

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Key words: deep radioactive waste repository, crystalline rock, migration, injection test, gas conductivity, permeability

Ključne riječi: duboko geološko odlagalište radioaktivnog otpada, magmatske stijene, migracija, injekcijsko ispitivanje, propusnost plina, propusnost.

Abstract

The study of gas migration in crystalline rock using injection tests is being carried out in the frame of the FORGE (Fate of Repository Gases) project. The Czech Technical University in Prague (CTU), Centre of Experimental Geotechnics (CEG) is participating in WP4 which is focused on disturbed host rock formations with respect to radioactive waste deep repositories. A series of in-situ tests is being conducted at the Josef Underground Laboratory. The aim of the testing is to simulate and study phenomena that might lead to gas-driven radionuclide transport in fractured crystalline rock. The in-situ tests combine migration and large-scale gas injection measurements; gas injection tests are being employed for the study of gas transport. For the purposes of comparison of the behaviour of the rock mass with regard to air and water a series of water pressure tests are also being carried out. The quality of the rock mass is assessed using rock mass classification systems.

Sažetak

Ispitivanje migracije plinova u kristaliničnoj (magmatskoj) stijeni primjenom injekcijskog ispitivanja provodi se u okviru FORGE projekta (Fate of Repository Gases - Sudbina odlagališnih plinova). Centar za eksperimentalnu geotehniku (CEG - Centre of Experimental Geotechnics) Češkog tehničkog sveučilišta u Pragu (CTU - The Czech Technical University in Prague) sudjeluje u WP4 koji se bazira na razlomljenim formacijama stijene vezano uz duboka geološka odlagališta radioaktivnog otpada. U podzemnom laboratoriju Josef provodi se serija in situ ispitivanja. Cilj ispitivanja je simulacija i proučavanje fenomena koji mogu dovesti do transporta radionuklida kroz razlomljenu magmatsku stijenu pomoću plina. In situ ispitivanja kombiniraju migraciju i mjerenja injektiranja plina u velikom mjerilu; ispitivanja injektiranja plina koriste se za ispitivanje transporta pomoću plina. Za svrhu usporedbe ponašanja stijenske mase pod djelovanjem zraka ili vode proveden je niz ispitivanja. Kvaliteta stijenske mase se procjenjuje korištenjem sustava za klasifikaciju stijenske mase.

1. Introduction

The study of gas migration in crystalline rock using injection tests is being carried out in the frame of the FORGE (Fate of Repository Gases) project. The Czech Technical University in Prague (CTU), Centre of Experimental Geotechnics (CEG) is participating in Work Package 4 which is focused on disturbed host rock formations with respect to RAW deep repositories. A series of in-situ tests are being conducted at the Josef Underground Laboratory as part of the project. The aim of the testing is to simulate and study phenomena that might lead to gas-driven radionuclide transport in fractured (Excavation Damaged/Disturbed Zone - EDZ) crystalline rock. One of the various deep repository construction concepts currently being considered envisages crystalline (granite) formations as the host rock environment. Certain sections of the Josef Underground Laboratory are located in similar rock environments and therefore provide suitable conditions for the research. The Josef facility consists of an underground laboratory complex created by means of the reconstruction of the former Josef exploratory gold mine the galleries of which were excavated using the drill and blast method which would suggest that there is a wide range of EDZs which will allow the study of the differences between disturbed near-field and undisturbed host rock environments.

1.1. Josef Underground Laboratory

The Josef gallery (Fig. 1) runs in a NNE direction across the Mokrsko hill rock massif. The total length of the main drift is 1836m, with a cross-section of 14–16m^2. The overlying rock thickness is 90–150m. The main exploration gallery is connected to various exploration workings by a number of insets which follow ore formations and provide access to two further levels. The total length of the galleries is approximately 9km; 90% of the breakings are not fitted with linings. The end of the main gallery is connected to the ground surface by means of an unsupported 110m vent.

The underground complex consists of two main sections (Celina and Mokrsko). Celina and the eastern part of Mokrsko are situated in tuffs and vulcanites of the Jilovske belt (Morávek, 1992). Most of the western section of Mokrsko lies in granodiorite of the Central Bohemian Pluton.

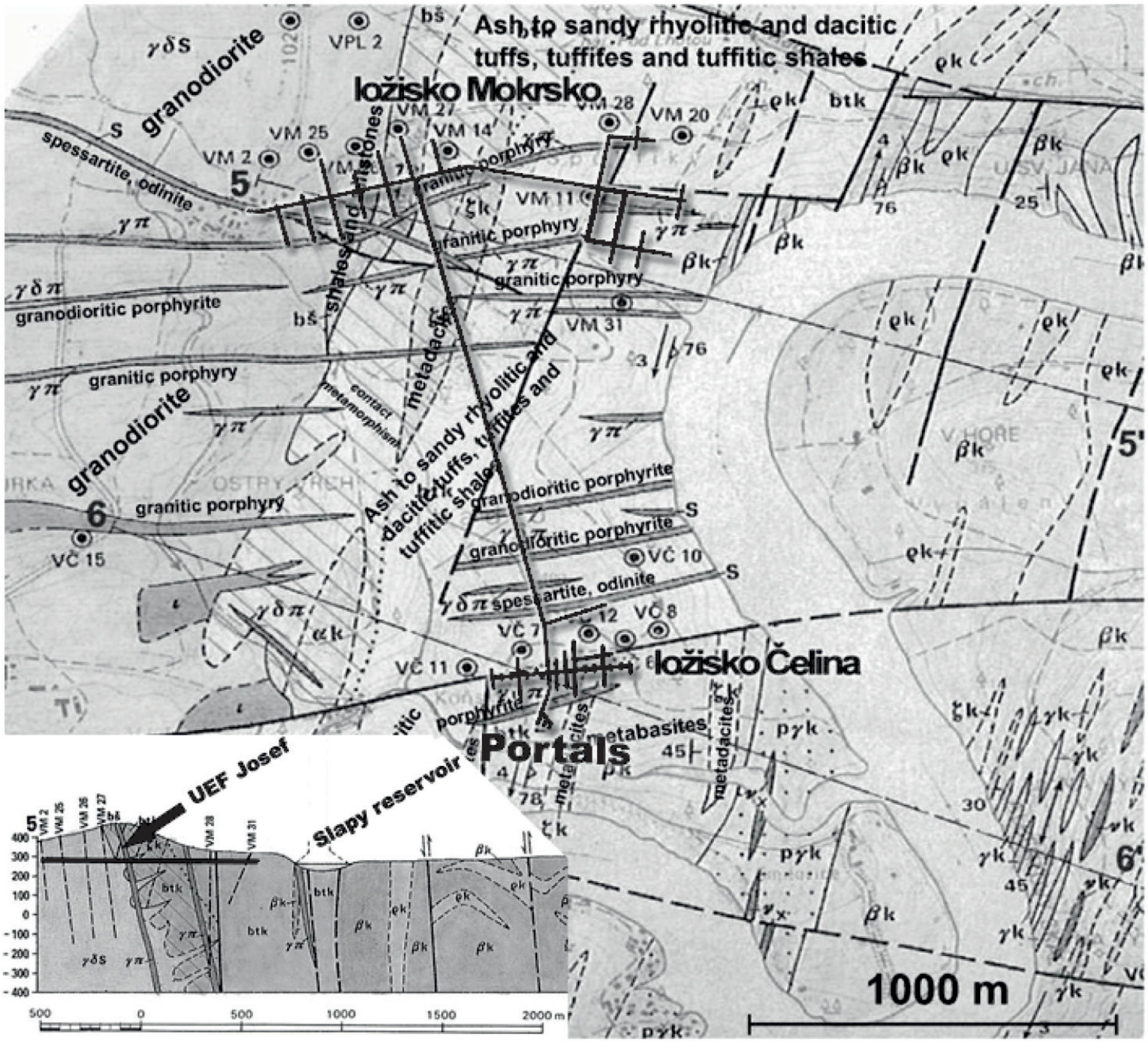

Figure 1. Geology of the Josef Underground Laboratory

Slika 1. *Geologija podzemnog laboratorija Josef*

2. In-situ testing

The series of in-situ tests combine migration and large-scale gas injection measurements; gas injection tests are being employed for the study of gas transport. The testing principle consists of injecting gas into a sealed borehole in the rock mass and monitoring property changes over time. The custom-made measuring instrumentation consists of a probe, measuring apparatus, a gas reservoir and a compressor (Fig. 2). Compressed air is used as the gaseous medium and is supplied by means of a high pressure compressor. Air is injected into the borehole which is sealed by means of a packer system consisting of a single or double packer. The measuring apparatus is designed to function as a mobile measuring station and features gas pressure level control and the automatic registration of pressure, temperature and gas volume. The control and recording software runs on a laptop connected to the apparatus.

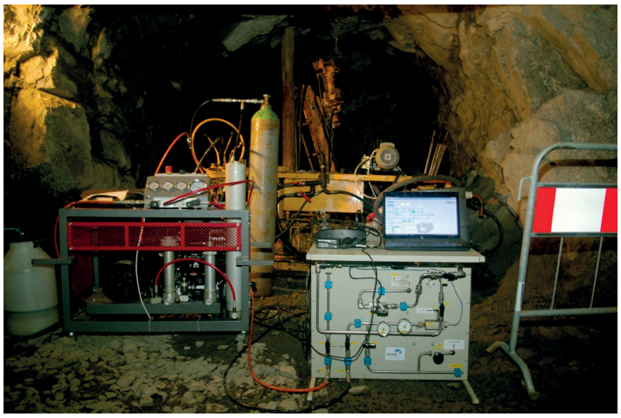

Figure 2. Test equipment
Slika 2. *Oprema za ispitivanje*

2.1. Test types

Based on the study of available scientific data from similar experiments carried out elsewhere (Bauer et al., 1995; Jakubick and Franz, 1993; Royle, 2002) and discussions with the apparatus manufacturer a total of three tests are being carried out. The testing methodology of the first (the Constant Head Injection Test - CHIT) is based on pressurising the borehole to achieve the maximum viable pressure at a steady flow state (steady pressure and flow rate). The flow rate of air into the borehole is directly dependent on the pressure at the point of input of the measuring apparatus. The maximum possible flow rate is around 40 normal litres per minute. The pressure drop test (PDT) begins immediately after the CHIT. Injection is halted following stabilisation of the air flow upon which the pressure drop curve is observed. The test ends when the pressure in the borehole becomes stabilised. The measurement apparatus also allows the measurement of outflow from the rock mass. The flow path through the measuring device is changed following pressurisation of the borehole and stabilisation of the air flow upon which the outflow from the borehole is measured. This test allows the comparison of the amount of air flowing into and then back from the rock mass.

2.2. Pilot testing

A total of four sites, with differing geological conditions, were used for pilot testing purposes. Horizontal boreholes, with a diameter of 57mm, were drilled at each location and rock mass classification systems were used in order to assess the quality of the rock mass at each of these locations. A series of preliminary experiments were performed in order to verify the characteristics of the rock mass in situ and for testing and subsequent approval of the setup and methodology of the apparatus. Baseline permeability measurements of the rock in the vicinity of the injection boreholes were obtained by means mainly of CHIT and PDT techniques. As part of the pilot testing stage, various types of tests, both short- and long-term, were performed on different injection sections using the single packer system. The short-term tests consisted of a series of repeated injection pulses lasting from tens of minutes to several hours; the long-term tests included the monitoring of the changes in flow during injection testing lasting from several days to one week.

2.3. Main field tests

The main field tests are being conducted in a specially sunk vertical borehole drilled into the granodiorite rock area of the Josef facility (Mokrsko-West). The method used for the research of the permeability of the disturbed zone consists of the gradual deepening of the vertical borehole and the measurement of gas permeability using local gas pressure testing methods. In the first phase the borehole was drilled to a depth of 19.69m and, following the performance of pressure tests, was extended to a depth of 30.10m. The borehole was systematically tested using pressure testing methods following which it is planned that it will be extended further to a depth of 40m. The permeability of individual sections of the borehole was tested depending on the depth of the packer in the borehole during the gas injection process.

In order to investigate differences between gas and water a series of water pressure tests was conducted in the vertical borehole MW-SP67-3V (the first phase length19.69m) using the single-packer system at three levels (depth of the packer: 15m, 10m and 2m) and for different pressure levels (input pressures: 10, 20, 25 and 30bar). The duration of each pulse was approximately 15 minutes. The instrumentation used consisted of a high-pressure piston pump with a maximum pressure of 20MPa and a performance level of 5 litres per minute. Water consumption was determined by monitoring the drop in water level in the plastic cylinder by means of a digital water level gauge.

2.4. Results

2.4.1. Gas injection tests results

The area of experimental interest consists of igneous rock (biotite granodiorites of the Central Bohemian Pluton). The rock is characterised by a certain intensity of jointing and, in the vertical direction, is crossed by venous rocks. In addition to natural jointing, the rock was disturbed in the area around the open underground spaces as a result of construction excavation work the technology employed for which consisted of drilling and blasting. Consequently, a broad EDZ was created in the vicinity of the drifts which affects the permeability of the rock mass up to distances of several meters. The gas permeability of the intact granitic rock at a load corresponding to approximately the primary stress level in the test locations is in the order of 10-18 to 10-20 m^2 (Hokr et al., 2007). Following rock mass classification systems were used in order to assess the quality of the rock mass at location: RQD (Rock Quality Designation), Q method, RMR (Rock Mass Rating), RMi (Rock Mass Index) (Svoboda, Smutek; 2010).

Intrinsic permeability and gas conductivity were determined based on the measured data obtained from the Constant Head Injection tests. Generally, the permeability (also known as the intrinsic permeability) of the rock is determined by the distribution and volume of the pores in terms of porous rock, or by the features of the joints with regard to jointed rock masses and is independent of the fluid. Gas conductivity, on the other hand, is a function of both the medium and the fluid and refers to the ability of a rock to transmit gas. It is possible to calculate gas conductivity from intrinsic permeability and vice versa on the basis of known fluid characteristics. The relationships between permeability and conductivity is given by equation (1).

$$K_g = \frac{k \rho_g g}{\mu_g} \qquad (1)$$

where:

- K_g gas conductivity [m/s]
- k intrinsic permeability of rock [m^2]
- ρ_g density of gas [kg/m^3]
- g gravity acceleration [m/s^2]
- μ_g dynamic viscosity of gas [kg/(m.s)]

A simplified radial 2D model of flow (cylindrical) was considered for the calculation of intrinsic permeability. The total flow rate is given by equation (2).

$$Q = \frac{\Delta(p^2)}{p_0 \ln(\frac{R}{r})} \pi L \frac{k}{\mu} \qquad (2)$$

where:

- Q flow rate [m^3/s]
- k intrinsic permeability [m^2]
- Δp difference between pressures [Pa]
- P_0 reference pressure (atmospheric) [Pa]
- r radius of the borehole [m]
- R effective radius (radius of influence) [m]
- L the length of the borehole section (injection zone) [m]

Figure 3 shows the intrinsic permeability and gas conductivity results from individual sections of the borehole calculated by means of the measured data. In addition, the recalculation of the permeability of each borehole section was carried out based on the difference between the two adjacent measurements (values in italics in Fig. 3). The dependence of these values of permeability on the depth of the borehole is shown in Fig. 4.

The results reveal a decreasing trend in permeability with distance from the gallery. The permeability of the closest part of the rock mass to the gallery is most affected by the EDZ.

The first sections (the first 4 points on the graph) further confirmed the trend that permeability declines with increasing depth and distance from the gallery (a decrease of one order of magnitude to approximately 5 meters). Furthermore, surprisingly, an increase in permeability occurred with increasing depth which was probably due to the presence of longitudinal fractures within the borehole and interconnected joint systems which caused injected air to leak back into the borehole.

The calculation considers the homogenization of the rock mass and in the case of the presence of a local fracture communicating with the back unsealed part of the borehole or directly with the gallery the results are biased. When calculating the permeability of the relevant parts of the borehole, negative permeability values were obtained and these results were subsequently discarded. The trend of decreasing permeability was again confirmed more deeply within the rock mass; values obtained of around 10-20 m2 at a depth of over 25m correspond to the order of permeability of intact granitic rock.

The data from the pilot tests in the horizontal boreholes was also used to assess the development of permeability with depth; however the decreasing trend was not confirmed. Due to their shallow depth (up to 20 meters) as well as to the natural high degree of jointing of the rock mass, the intensity of which did not change significantly with depth, major differences in permeability were not detected.

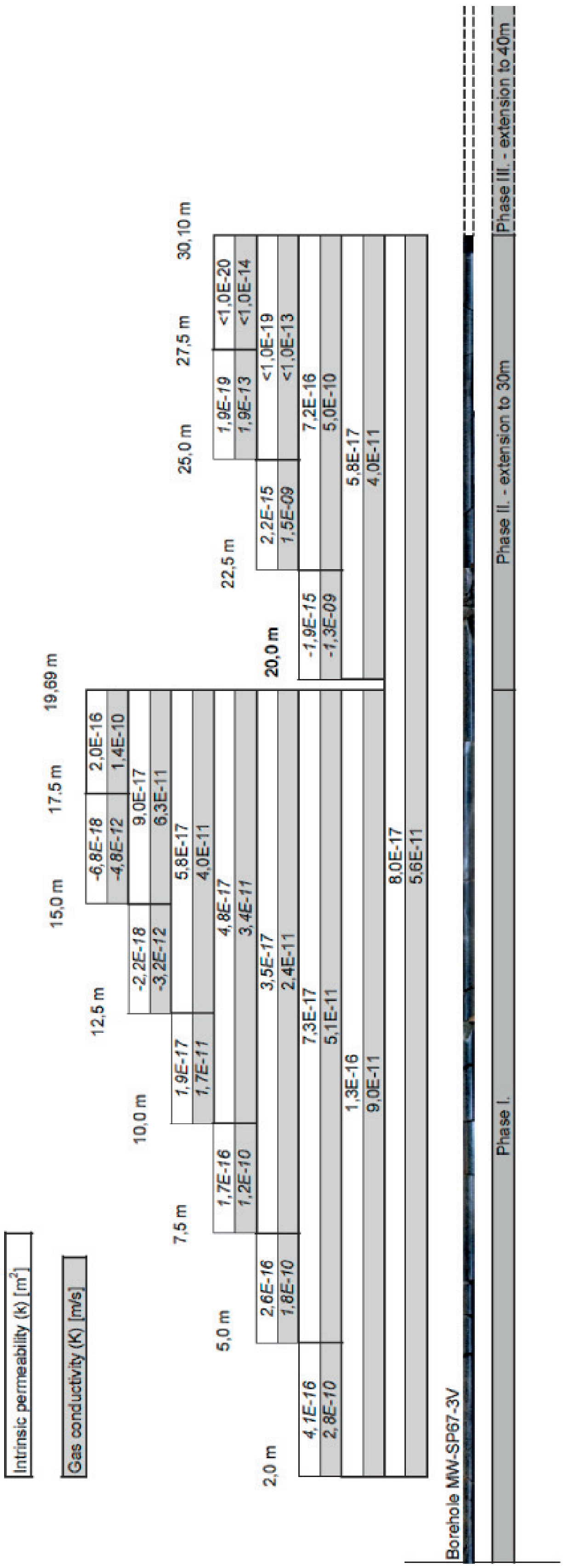

Figure 3. Results of the gas permeability tests at the MW-SP67-3V borehole

Slika 3. *Rezultati ispitivanja propusnosti na plin u bušotini MW-SP67-3V*

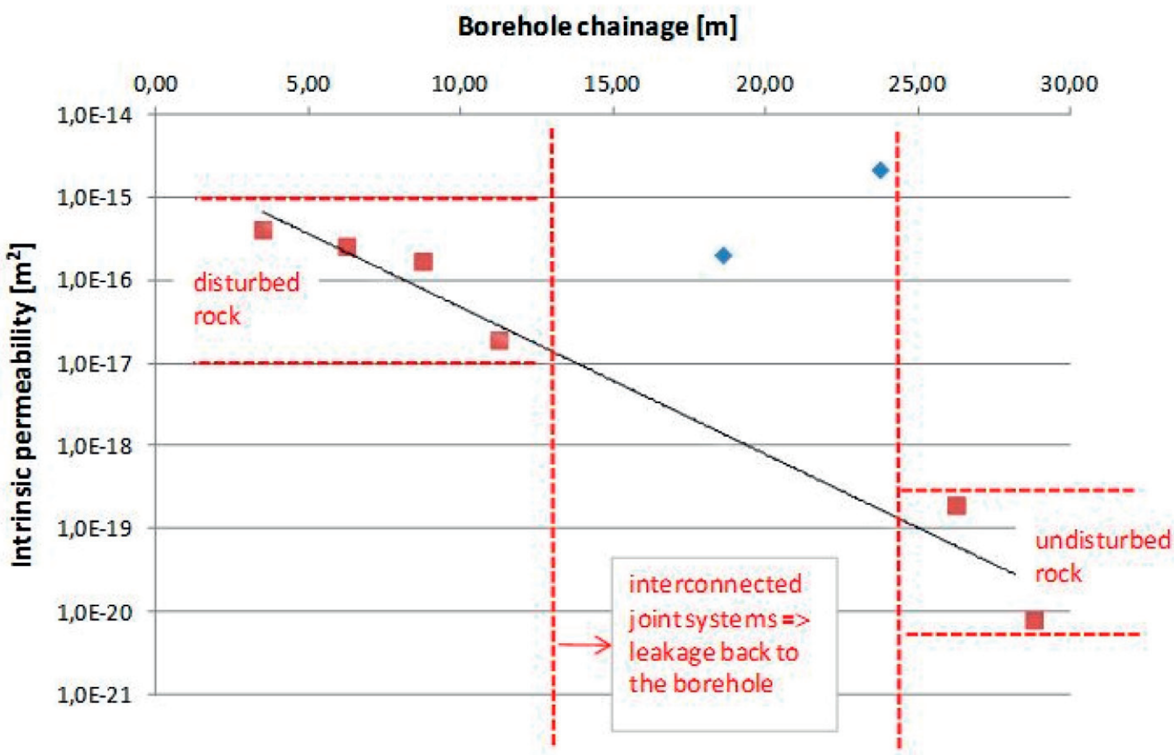

Figure 4. Dependence of permeability on distance from the gallery

Slika 4. *Ovisnost propusnosti o udaljenosti od galerije*

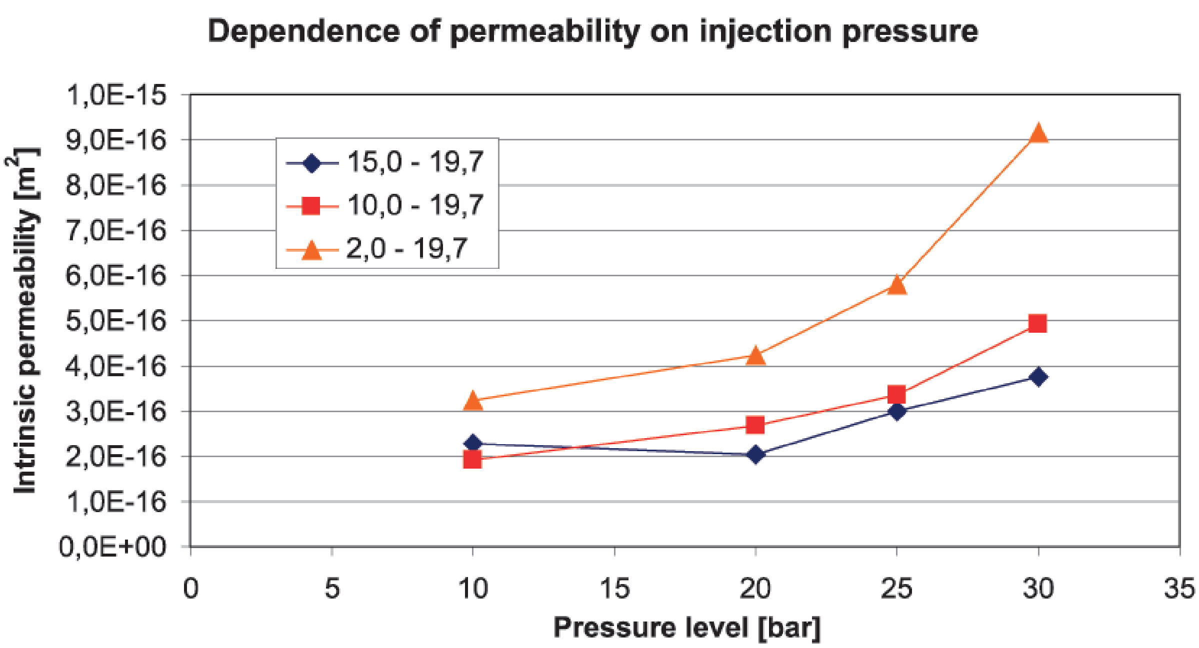

Figure 5. Water injection tests results

Slika 5. *Rezultati ispitivanja injektiranja vode*

2.4.2. Water injection tests results

The similar flow model as used in the gas tests was used for evaluation of water pressure tests. Fig.5 shows the dependence of calculated intrinsic permeability on the injection pressure level. A value of pressure around 25 bar, which matches the primary stress level, should coincide with increasing permeability (pathway dilatation).

3. Conclusions

The aim of this part of the project was to determine baseline hydraulic measurements in crystalline rock structures. The first pilot tests were conducted in four horizontal boreholes. A vertical borehole was used for detailed testing in the granite area of the Josef Underground Facility. The use of the gradual extension method and the measurement of developments within the vertical borehole confirmed a decreasing trend in permeability away from the EDZ in the vicinity of the gallery. To what extent the rock mass is influenced (injected air communicates with the surrounding gallery through the joint systems) may yet be confirmed by the results of the latest phase of testing in the vertical borehole (extension to a depth of 40 meters).

4. Acknowledgement

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