ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Gas permeability of rocks and its use for monitoring crack propagation during compressive strength testing

M. Vavro, L. Vavro & L. Kubina
The Czech Academy of Sciences, Institute of Geonics, Ostrava, Czech Republic
martin.vavro@ugn.cas.cz (email of corresponding author)

Abstract

The microstructure of pores in rocks includes the shape, size, volume distribution and connectivity of pores and cracks and has a significant influence on large number of properties such as the strength of the rock, its deformation and fracture behaviour. Together with the related rock permeability, it is the decisive factor in assessing the suitability of the rock host environment for demanding technical applications such as the geological disposal of high-level radioactive waste or carbon sequestration. The rock permeability therefore not only reflects the physical and petrographical properties of the rock material itself, but also depends on the intensity of the rock failure. The state of stress that leads to the closing of the pore system reduces the rock permeability. Conversely, the rock damage processes induced by continued loading cause the origin and development of cracks, which often very significantly increases the rock permeability. This close relationship between the permeability of the rock to fluids and the stress state, respectively the degree of failure of the rock material, thus means that the change in permeability coefficient values during loading can be used as a very sensitive indicator for measuring the progress of the failure process of test specimen. Five different types of rocks were used for observing the changes in gas permeability during compressive loading, including conglomerates, sandstones and migmatite. The permeability measurement equipment consists of a KTK 100 triaxial chamber adapted for the passage of gas. The ZWICK 1494 mechanical press was used as a source of axial stress. The measurements were carried out on cylindrical test specimens with a diameter of 48 mm and a height of 96 mm. It was found that an increase in gas permeability due to the formation of microcracks occurs when ca 70-90 % of the maximum loading force is applied.

Keywords

Rock microstructure, gas permeability, triaxial compression test, crack propagation, failure process

ISRM

NBG

1 Introduction

Textural aspects of the rock such as porosity, pore microstructure and related rock permeability as well as rock fabric anisotropy are crucial factors when assessing the suitability of the rock environment for such serious engineering challenges as high-level radioactive waste disposal, natural gases production and/or carbon dioxide sequestration (Delay et al. 2014; Goral et al. 2020; Liu et al. 2018; Zhao et al. 2022). Pore microstructure in rocks regards size, shape, volume concentration, distribution and connectivity of pores and cracks and has a substantial impact on many macroscopically observed properties such as rock strength and its deformation and fracture behaviour (Zhang and Wong 2018). It follows from the above that effective porosity and permeability are two absolutely fundamental parameters used to characterize not only porous media, but all rocks in general. Both properties represent inherent parameters, but their values determined by measurement are not only influenced by the rock itself but also depend on fluid properties and test conditions (Tan et al. 2013).

It is moreover obvious that porosity and permeability reflect not only petrography, microstructure and physical properties of the rock, but they are also very sensitive to the stress state and the degree of rock failure (Konečný and Kožušníková 1996; Konečný and Kožušníková 2011; Luo et al. 2011; Yang et al. 2007; Zhao et al. 2022). Two different phases are very well distinguishable throughout the rock permeability evolution during the whole stress-strain process. In the first stage, permeability decreases as a result of axial compression due to closure of the rock pore space. In the second phase, microcracks develop in the test specimen, which represent important paths for the passage of the filtration media, thus the rock permeability increases. Finally, when the tested rock fails, the increase in permeability is very high and can reach several times the initial permeability value (Kožušníková and Konečný 2011; Wang et al. 2022).

The well-known and above-described close relationship between the permeability of rock for fluids and the stress state, or the degree of failure of the rock material also means that the changes of the permeability coefficient during loading can be successfully used as a very sensitive indicator to assess the progress in the failure process of test specimen. Therefore, the main objective of the presented research was to determine the stress level at which cracks initiate and propagate within the rock, on the basis of continuously measured changes in rock permeability during loading. Five different rocks from conglomerate, sandstone and migmatite groups were used for this purpose.

2 Rock material and test specimens used for experiment

The following types of sedimentary and metamorphic rocks were used for observing changes in permeability during loading: (i) coarse grained sandstone to sandy conglomerate from the former Lazy hard coal mine, (ii) medium-grained sandstone from the former Staříč hard coal mine (Vavro et al. 2019), (iii) fine- to medium grained glauconitic sandstone from the Řeka quarry, often referred to in literature as Godula sandstone (Vavro et al. 2016), (iv) fine- to medium-grained quartz sandstone from the Kocbeře quarry (Kytýř et al. 2024; Vavrik et al. 2021), and (v) stromatic migmatite from the former Rožná I uranium mine (Bukovská et al. 2019; Souček et al. 2017).

Physical and mechanical properties of studied rocks are presented in Table 1.

Table 1 Mean values of selected physico-mechanical parameters of rocks used for experiment (according to own measurements and data published in above mentioned literature)

Rock property	**Lazy sandstone**	**Staříč sandstone**	**Řeka sandstone**	**Kocbeře sandstone**	**Rožná migmatite**
Bulk density [$kg \cdot m^{-3}$]	2480	2520	2530	2210	2740
Total porosity [vol. %]	7.7	5.7	5.9	14.3	0.7
Open porosity [vol. %]	6.9	5.1	5.5	10.6	0.4
Water absorption capacity [wt. %]	3.0	1.5	2.1	4.2	0.1
Ultrasonic wave velocity [$km \cdot s^{-1}$]	3.37	3.56	3.83	3.21	4.48
Uniaxial compressive strength [MPa]	108	151	126	72	122
Splitting tensile strength [MPa]	5.1	7.0	5.7	4.0	10.3

Note: strength properties were tested on dried test specimens

Selected rocks include representatives of building and sculpture stones, sediments of coal-bearing formations of the Upper Silesian Coal Basin as well as rocks from the Bukov underground research facility. To measure rock permeability, standard test specimens with diameter (*D*) of 48 mm and length (*L*) of 96 mm, i.e. with slenderness (*L/D*) ratio of 2.0 were drilled from the rock blocks. In the case of Lazy, Staříč and Kocbeře sandstones, core drilling was carried out perpendicular to the sandstone bedding planes. For the Godula sandstone, test specimens were prepared in two directions with respect to the rock fabric anisotropy, both perpendicular and parallel to the bedding surface. In the following text, the drilling direction parallel to bedding planes will be designated by the letter "P", the samples with the designation letter "K" were prepared perpendicular to rock bedding. In the case of Rožná migmatite, drilling was performed in the direction oblique (ca 45°) to the metamorphic foliation.

3 Measuring equipment and methodology of the experiment

The main constituent part of laboratory equipment for measuring gas permeability of rocks is represented by a KTK 100 triaxial cell (UNIPRESS, Poland) modified for gas passage. Basically, it is the so-called "false triaxial apparatus", where the confining pressure ($\sigma_2 = \sigma_3$) is applied to the test specimen through hydraulic oil pressure which, with the current design of the device, can reach a value of up to 30 MPa. The source of axial stress (σ_1) is the computer-controlled mechanical press ZWICK 1494 (Zwick/Roell, Germany) with the maximum force of 600 kN. Nitrogen is used as the gas medium for permeability measurements. Due to its properties and the short duration of the experiment, nitrogen can be considered an inert gas, which does not react with the rock material.

The device allows two methods of measurement, namely permeability measurement during the increase of hydrostatic (confining) pressure and permeability measurement with axial stress increasing. A more detailed procedure and measurement conditions for both of these methods are given in Konečný and Kožušníková (1996), Konečný and Kožušníková (2011) and/or Kožušníková and Konečný (2011). For the purposes of presented experiment, the measurement regime at a constant confining pressure and increasing axial stress was applied. In this case, the test specimen was covered with a rubber membrane, then clamped in jaws of the press machine and the confining pressure was set to the required value of 3 MPa. Subsequently, the axial stress was gradually increased by the movement of the press jaws ($\sigma_1 > \sigma_2 = \sigma_3$) up to the failure of the test specimen. Throughout the duration of the experiment, the nitrogen pressure was regulated from the gas pressure vessel using the control valve so that it was kept at the required value of 3 MPa. For this type of experiment with continuous measurement of the volume of passed gas, it was necessary to measure the flow values at regular intervals, which was ensured by using several flow meters with different ranges. The volume flow of nitrogen was measured and permeability was assessed using Darcy's law (ASTM 1990). A diagram showing the measuring equipment is presented in Fig. 1.

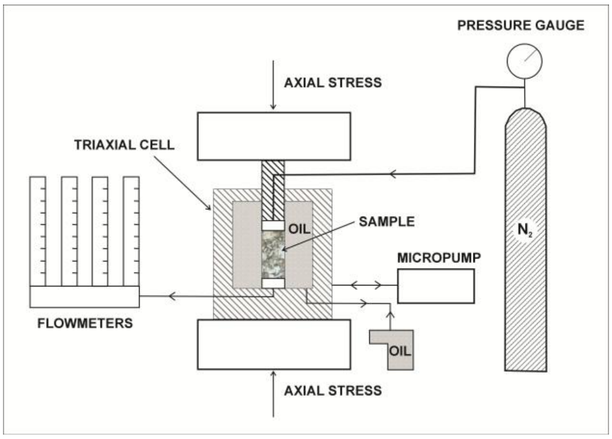

Fig. 1 Diagram of the equipment for measuring gas permeability

4 Experimental results

The results of the measuring gas permeability of rocks during loading with the aim of using gas permeability as an indicator of the moment from the crack begins to propagate are shown in Fig. 1 to Fig. 5. Overall evaluation of measurement results in the form of determining the level of the loading force required for crack initiation and propagation is presented in Table 2.

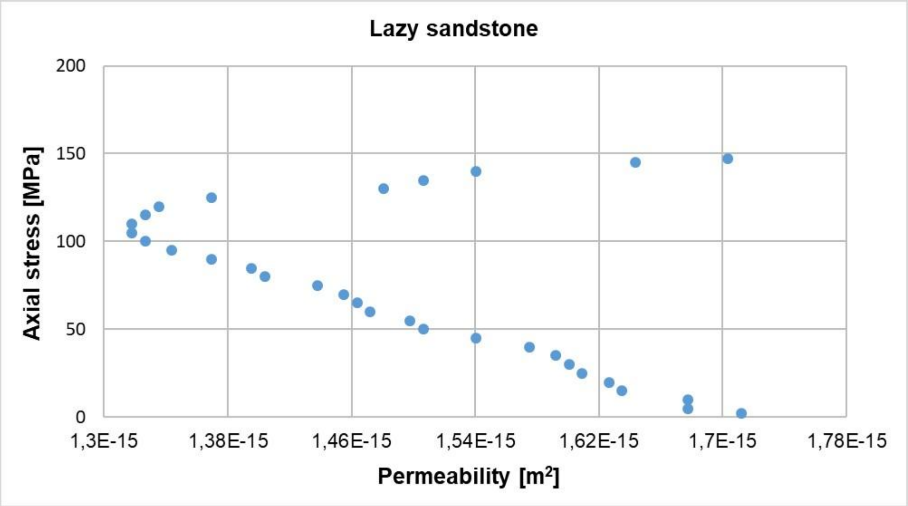

Fig. 1 Influence of increasing axial stress on gas permeability for Lazy sandstone

From Fig. 1 it is evident that during loading the sandstone from the Lazy mine, its pore space gradually closes, while from the level of 115 MPa, on the contrary, a significant increase in gas permeability is visible.

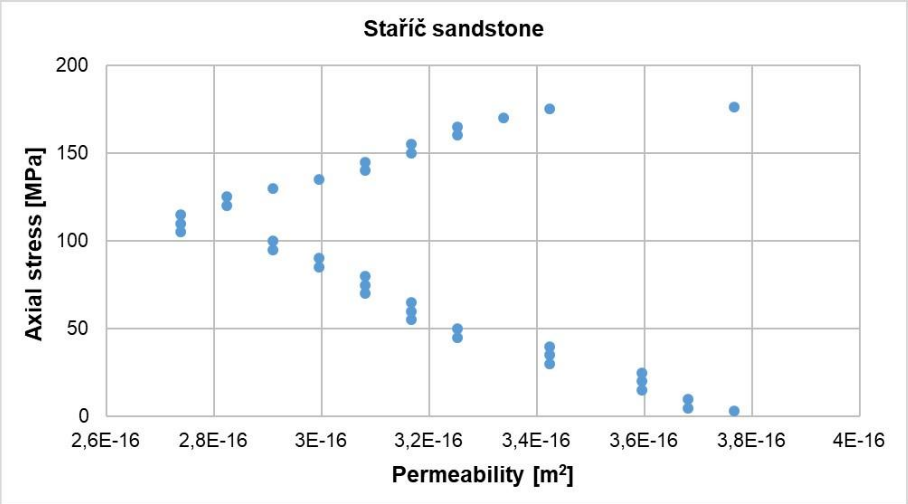

Fig. 2 Influence of increasing axial stress on gas permeability for Stařič sandstone

As can be seen from Fig. 2, the gas permeability of the Stařič sandstone during loading is very similar to the behavior of the Lazy sandstone (Fig. 1). Even here, the pore space of the Stařič sandstone gradually closes during the first phase of loading, but from a value of 120 MPa, on the contrary, the gas permeability increases significantly due to the opening of microcracks.

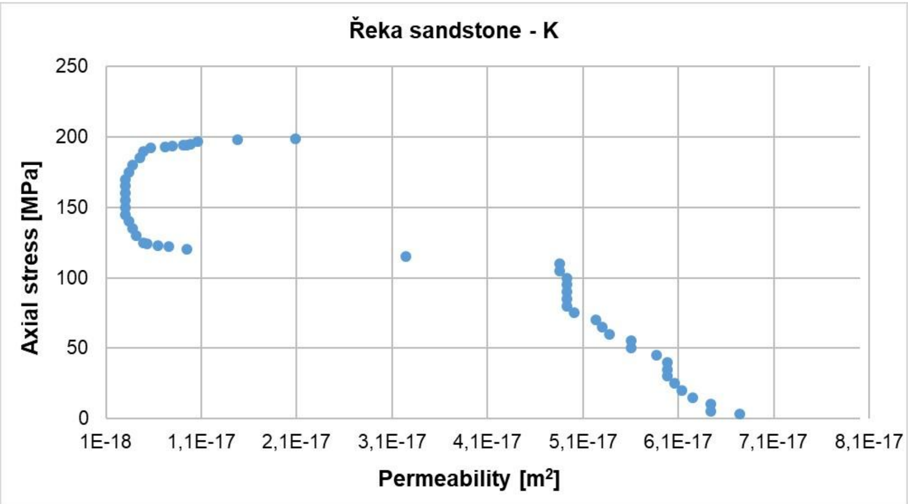

Fig. 3 Influence of increasing axial stress on gas permeability for Řeka sandstone (“K” direction)

Compared to the Lazy and Staříč sandstones, the Řeka sandstone shows a somewhat different course of gas permeability under loading. In the samples in the "K" direction (Fig. 3), the pore space is closed at about 120 MPa, while the gas permeability value does not change much up to a loading value of 175 MPa. The increase in permeability then occurs from the level of 175 MPa, until the sample ruptures.

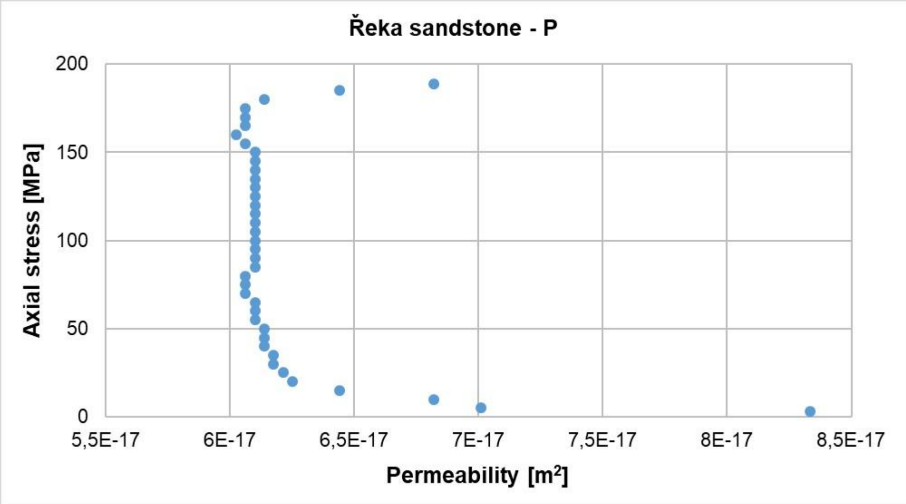

Fig. 4 Influence of increasing axial stress on gas permeability for Řeka sandstone ("P" direction)

In the P direction (Fig. 4), the gas permeability values of the Řeka sandstone decrease to a stress level of ca 40 MPa, then they are almost constant up to 165 MPa, when it then increases rapidly.

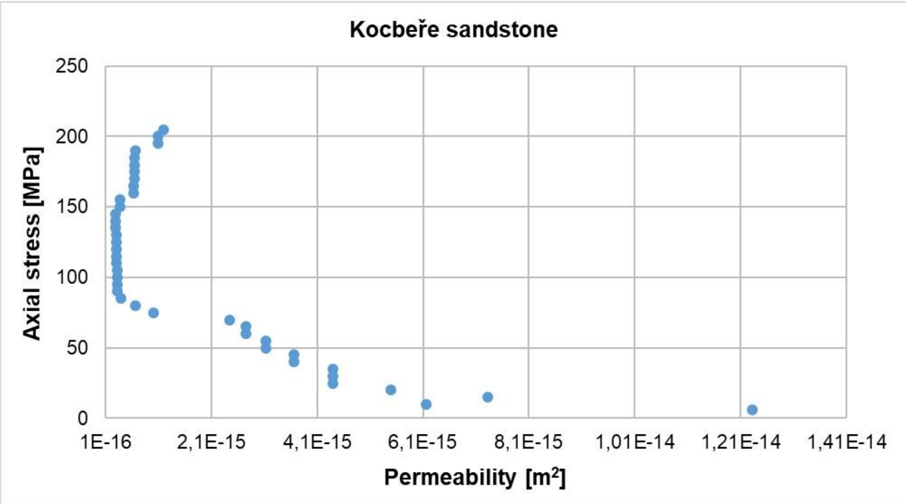

Fig. 5 Influence of increasing axial stress on gas permeability for Kocbeře sandstone

The Kocbeře sandstone (Fig. 5) is similar to the Řeka sandstone in terms of the delay between the decrease (ca 90 MPa) and increase (150 MPa) in gas permeability during loading.

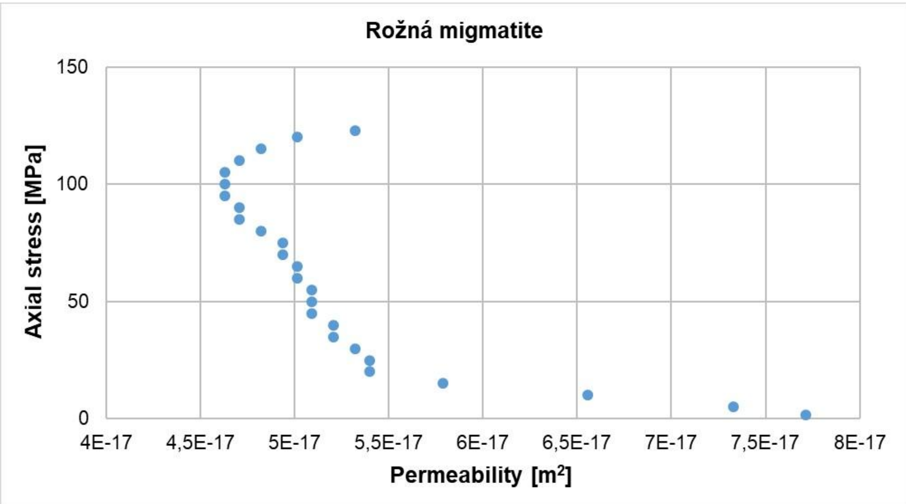

Fig. 6 Influence of increasing axial stress on gas permeability for Rožná migmatite

On the other hand, the Rožná migmatite is similar to the Lazy and Staříč sandstones in terms of gas permeability during the loading process. The pore space of the Rožná migmatite gradually closes, while from the level of 110 MPa, on the contrary, a significant increase in gas permeability is visible.

For each tested rock, the values of the maximum force at rock failure (F_{max}) and the force at which a significant increase in gas permeability occured thanks to the formation of cracks due to compression loading (F_{op}) are presented in Table 2. It is evident from the data that this significant increase in gas permeability of the rocks was found when approximately 70-90% of F_{max} was reached.

Table 2 Compressive strength on dried cylindrical and cubic test specimens

Rock	**Maximal loading force F_{max} [kN]**	**Crack opening force F_{op} [kN]**	**F_{op}/F_{max} ratio [–]**
Lazy sandstone	147	115	0.78
Staříč sandstone	176	120	0.68
Řeka sandstone “K”	199	175	0.88
Řeka sandstone “P”	189	165	0.87
Kocbeře sandstone	205	150	0.73
Rožná migmatite	123	110	0.80

5 Conclusions

The influence of the stress state, respectively the degree of failure during compressive loading on gas permeability was studied on five selected types of rocks encountered in construction and geotechnical practice. Despite their different origin and mineralogical composition, the studied rocks showed similar behavior to some extent regarding the influence of applied stress on gas permeability.

Based on the laboratory measurements, it can be stated that the stress which leads to the closing of the pore system at the same time reduces the gas permeability of the rock material. On the other side, material-disturbing processes induced by continuous and increasing loading cause the initiation of microcracks, which increases the ability of the rock material to pass fluids. This is subsequently manifested by an increase in permeability, often very significant.

The main findings obtained during this initial study can be summarized as follows:

- It was found that a significant increase in gas permeability due to the formation of microcracks occurs at a level of approximately 70-90% of the maximum loading force. This finding is fully consistent with data published, for example, by Zhang et al. (2020) for compression or by Zietlow and Labuz (1998), Vavřík et al. (2021) or Kytýř et al. (2024) for flexural loading mode.

- At the same time, it was shown that while in some studied rocks (Lazy and Staříč sandstones and Rožná migmatite) an increase in gas permeability occurs immediately after the previous reduction of pore space, in others (Řeka and Kocbeře sandstones) there is often a relatively long delay between these two phases.

- In the case of the Řeka sandstone, no significant effect of textural anisotropy in the form of sandstone bedding planes was found, either on the value of the maximum load at failure or on the force value at which gas permeability increases due to the formation of microcracks. However, this issue will be the subject of more detailed research in the future.

In this connection, the measuring changes in the gas permeability coefficient turned out to be sensitive method for determining the degree of the test specimen failure. It can thus represent an alternative to other methods to studying failure process in rocks such as acoustic emission or X-ray computed micro-tomography (Vavřík et al. 2021; Kytýř et al. 2024; etc.).

Acknowledgements

Presented research has been financially supported by the Czech Science Foundation within the project No. GA23-05128S. The authors of the paper also wish to thank the Lesostavby Frýdek-Místek a.s., DIAMO s.p., and KOKAM Ltd. companies for providing rock samples for our study.

References

ASTM (1990) Standard test method for permeability of rocks by flowing air (ASTM D4525-90). ASTM International, West Conshohocken, PA, USA.

Bukovská Z, Soejono I, Vondrovic L, Vavro M, Souček K, Buriánek D, Dobeš P, Švajgera O, Waclawik P, Řihošek J, Verner K, Sláma J, Vavro L, Koníček P, Staš L, Pécskay Z, Veselovský F (2019) Characterization and 3D visualization of underground research facility for deep geological repository experiments: A case study of underground research facility Bukov, Czech Republic. Engineering Geology 259: 105186. DOI: 10.1016/j.enggeo.2019.105186.

Delay J, Bossart P, Ling LX, Blechschmidt I, Ohlsson M, Vinsot A, Nussbaum C, Maes N (2014) Three decades of underground research laboratories: what have we learnt? Geological Society, London, Special Publications 400: 7–32. DOI: 10.1144/SP400.1.

Goral J, Panja P, Deo M, Andrew M, Linden S, Schwarz JO, Wiegmann A (2020) Confinement effect on porosity and permeability of shales. Scientific Reports 10: 49. DOI: 10.1038/s41598-019-56885-y.

Konečný P, Kožušníková A (1996) Measurement of gas permeability of coal and clastic sedimentary rocks under triaxial stress conditions. Geological Sociecty, London, Special Publication 109: 227–229. DOI: 10.1144/GSL.SP.1996.109.01.16.

Konečný P, Kožušníková A (2011) Influence of stress on the permeability of coal and sedimentary rocks of the Upper Silesian Coal basin. International Journal of Rock Mechanics and Mining Sciences 48(2): 347–352. DOI: 10.1016/j.ijrmms.2010.11.017.

Kožušníková A, Konečný P (2011) Influence of temperature on the permeability of rocks. Géotechnique 61(12): 1081–1085. DOI: 10.1680/geot.8.T.034.

Kytýř D, Koudelka P, Drozdenko D, Vavro M, Fíla T, Rada V, Vavro L, Máthis K, Souček K (2024) Acoustic emission and 4D X-ray micro-tomography for monitoring crack propagation in rocks. International Journal of Rock Mechanics and Mining Sciences 183: 105917. DOI: 10.1016/j.ijrmms.2024.105917.

Liu Y, Wang P, Yang M, Zhao Y, Zhao J, Song Y (2018) CO_2 sequestration in depleted methane hydrate sandy reservoirs. Journal of Natural Gas Scieence and Engineering 49: 428–434. DOI: 10.1016/j.jngse.2017.10.023.

Luo W, Qin YP, Zhang MM, Wang CX, Wang YR (2011) Test study on permeability properties of the sandstone specimen under triaxial stress condition. Procedia Engineering 26: 173–178. DOI: 10.1016/j.proeng.2011.11.2156.

Souček K, Vavro M, Staš L, Vavro L, Waclawik P, Konicek P, Ptáček J, Vondrovic L (2017) Geotechnical characterization of Bukov Underground Research Facility. Procedia Engineering 191: 711–718. DOI: 10.1016/j.proeng.2017.05.236.

Tan X (2013) Hydromechanical coupled behavior of brittle rocks – Laboratory experiments and numerical simulations. Dissertation at Technische Universität Bergakademie Freiberg, Freiberg, Germany.

Vavrik D, Benes P, Fila T, Koudelka P, Kumpova I, Kytyr D, Vopalensky M, Vavro M, Vavro L (2021) Local fracture toughness testing of sandstone based on X-ray tomographic reconstruction. International Journal of Rock Mechanics and Mining Sciences 138:104578. DOI: 10.1016/j.ijrmms.2020.104578.

Vavro L, Malíková L, Frantík P, Kubeš P, Keršner Z, Vavro M (2019) An advanced assessment of mechanical fracture parameters of sandstones depending on the internal rock texture features. Acta Geodynamica et Geomaterialia 16(2):157–168. DOI: 10.13168/AGG.2019.0013.

Vavro M, Vavro L, Martinec P, Souček K (2016) Properties, durability and use of glauconitic Godula sandstones: a relatively less known building stone of the Czech Republic and Poland. Environmental Earth Sciences 75(22): 1437. DOI: 10.1007/s12665-016-6248-3.

Yang Y, Song Y, Chen S (2007) Test study on permeability properties of coal specimen in complete stress-strain process. Rock and Soil Mechanics 28: 381–385.

Wang X, Zhou H, Zhang L, Preusse A, Xie S, Hou W (2022) Research on damage-based coal permeability evolution for the whole stress-strain process considering temperature and pore pressure. Geomechanics and Geophysics for Geo-Energy and Geo-Resources 8(5): 149. DOI: 10.1007/s40948-022-00464-5.

Zhang GK, Li HB, Wang MY, Li XF (2020) Crack initiation of granite under uniaxial compression test. Journal of Rock Mechanics and Geotechnical Engineering 12(3): 656–666. DOI: 10.1016/j.jrmge.2019.07.014.

Zhang Y, Wong LNY (2018) A review of numerical techniques approaching microstructures of crystalline rocks. Computer and Geosciences 115: 167–187. DOI: 10.1016/j.cageo.2018.03.012.

Zhao Y, Konietzky H, Frűhwirt T, Zhou HW (2022) Gas permeability evolution of coal with inclusions under triaxial compression – Lab testing and numerical simulations. Materials 15: 8567. DOI: 10.3390/ma15238567.

Zietlow WK, Labuz JF (1998) Measurement of the intrinsic process zone in rock using acoustic emission. International Journal of Rock Mechanics and Mining Sciences 35(3): 291–299. DOI: 10.1016/S0148-9062(97)00323-9.