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MIROSŁAW WIERZBICKI*, PAVEL KONEČNÝ**, ALENA KOŽUŠNÍKOVÁ***

PERMEABILITY CHANGES OF COAL CORES AND BRIQUETTES UNDER TRI-AXIAL STRESS CONDITIONS

PRZEPUSZCZALNOŚĆ RDZENI ORAZ BRYKIETÓW WĘGLOWYCH W TRÓJOSIOWYM STANIE NAPRĘŻENIA

The paper is dealing with the permeability of coal in triaxial state of stress. The permeability of coal, besides coal's methane capacity, is the main parameter determining the quantity of methane inflow into underground excavations. The stress in a coal seam is one of the most important factors influencing coal permeability therefore the permeability measurements were performed in tri-axial state of stress. The hydrostatic three-axial state of stress was gradually increased from 5 MPa with steps of 5 MPa up to a maximum of 30 MPa. Nitrogen was applied as a gas medium in all experiments.

The results of the permeability measurements of coal cores from the "Zofiówka" mine, Poland, and three mines from the Czech Republic are presented in this paper. As a "reference", permeability measurements were also taken for coal briquettes prepared from coal dust with defined porosity.

It was confirmed that the decreasing porosity of coal briquettes affects the decreasing permeability. The advantage of experimentation on coal briquettes is its good repeatability.

From the experimental results, an empirical relation between gas permeability and confining pressure has also been identified. The empirical relation for coal briquettes is in good correspondence with published results. However, for coal cores, the character of change differs. The influence of confining pressure has a different character and the decrease in permeability is stronger due to the increasing confining pressure.

Keywords: coal, gas permeability, tri-axial stress, coal briquettes

Przepuszczalność węgla, oprócz pojemności sorpcyjnej względem metanu jest głównym parametrem określającym dopływ metanu do podziemnych wyrobiskach górniczych. W warunkach naturalnych wartość przepuszczalności jest ściśle związana ze stanem naprężenia w pokładzie węgla. W pracy przedstawiono wyniki pomiarów przepuszczalności wykonanych w trójosiowym stanie naprężenia. Hydrostatyczny trójosiowy stan naprężenia stopniowo zwiększano od 5 MPa do maksymalnie 30 MPa z krokiem wynoszącym 5 MPa. Maksymalne ciśnienie hydrostatyczne odpowiada ciśnieniu hydrostatycznemu jakie występuje w górotworze nienaruszonym na głębokości około 1200 m. Pomiary przeprowadzono z zastosowaniem azotu na czterech rodzajach rdzeni węglowych. Trzy z nich pochodziły z kopalń czeskich (ČSM, Paskov,

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* STRATA MECHANICS RESEARCH INSTITUTE OF THE POLISH ACADEMY OF SCIENCES, UL. REYMONTA 27, 30-059 KRAKOW, POLAND

** INSTITUTE OF GEONICS AS CR, V. V. I., OSTRAVA, CZECH REPUBLIC

*** INSTITUTE OF CLEAN TECHNOLOGIES FOR MINING AND UTILIZATION OF RAW MATERIALS FOR ENERGY USE, INSTITUTE OF GEONICS AS CR, V. V. I., OSTRAVA, CZECH REPUBLIC

František) a czwarty z polskiej kopalni „Zofiówka". Własności węgli i miejsca ich pobrania zestawiono w tablicy 1. Dodatkowo, dla celów porównawczych wykonano pomiary przepuszczalności na materiale „wzorcowym" jakim są brykiety węglowe. Brykiety te wykonano metodą prasowania w urządzeniu pokazanym schematycznie na rys. 2. Własności brykietów zestawiono w tablicy 2, gdzie podano ich gęstości helowe, objętościowe oraz porowatości. Zmienność przepuszczalności wywołana zmianą naprężenia hydrostatycznego może być opisana równaniem empirycznym (3). Wartości przepuszczalności początkowej (dla $\sigma = 0$) oraz współczynników B z równania 3, dla różnych porowatości brykietów zestawiono w tablicy 3. Zaletą eksperymentów na brykietach węglowych jest ich powtarzalność. Zmienności przepuszczalności wywołane obciążeniem hydrostatycznym próbek, dla brykietów węglowych oraz rdzeni pokazano na wykresach z rysunku 4. W przypadku rdzeni węglowych zmienność przepuszczalności jest znacznie większa, co wynika prawdopodobnie z występowania szczelin i spękań widocznych na rys 1. Szczeliny te, jako główne drogi transportowe dla gazu przy niskich obciążeniach ulegają zaciśnięciu i część transportu gazu przenosi się do przestrzeni porowej.

Słowa kluczowe: węgiel, przepuszczalność gazowa, naprężenie trójosiowe, brykiety węglowe

1. Inroduction

The Upper Silesian Coal Basin (USCB) is a geological area located on the Czech-Polish border. It has an area of 6100 km^2. The USCB contains major deposits of coal in the Czech Republic and Poland (Martinec et al., 2005; Dopita, 1997; Kędzior, 2009). Coal mining in the region is threatened by methane. It increases with the depth of the mining work. (Lama & Bodziony, 1996). Coal and gas outbursts endanger workers in the coal mines in the Rybnik Coal Field, Poland, and in the Paskov Coal Mine in the Czech Republic. The increase in coal gas capacity and the depth of mining works changes the coal structure in the tectonic zones in the vicinity of faults, influencing the risk of outbursts (Rakowski et al., 1983). An example of outbursts that occurred in the vicinity of the tectonic zone with an altered coal structure (sheared coal) was the outburst in the "Zofiówka" Coal Mine in Poland in 2005. Wierzbicki and Młynarczuk (2006) carried out a detailed structural analysis of coal from this locality, both sheared coal and coal with a normal structure. Sorption properties of both materials were also determined (Wierzbicki & Dutka, 2010). Information on the properties of sheared coals can be found in Beamish and Crosdale (1998) and Cao et al. (2000). An important parameter influencing the start of an outburst is coal permeability (Li et al., 2003; Zhang, 1995). The third aspect in which permeability plays an important role is CO_2 sequestration in the coal seam. All of these factors indicate that the gas permeability of coal is one of the most important factors that influence the threat of methane and gas and coal outbursts in coal mines. The problems associated with methane in coal mines are among the most difficult problems that must be dealt with in modern mining.

2. Tested material

The study was performed on two types of materials. The first type of material were drill cores collected from a coal seam in the southern part of the USCB – Table 1. The test samples of coal cores from the Czech part of the USCB were taken from the three mine boreholes shown in Table 1. Sample No. 4312 is coal from the Prokop seam (Saddle members) (Martinec et al., 2005). This coal is typical banded dull coal with a high content of inertinite macerals (see Table 1). Sample No. 5216 is banded bright coal with a high content of vitrinite macerals. It was taken from seam 420 (Poruba members). The third sample, No. 5214, is banded bright coal with a high content of vitrinite macerals, but with a higher degree of coalification (R_r = 1.56%). Therefore, it is not possible to distinguish the liptinite macerals. This coal sample was taken from seam 047 (Petřkovice members). Sample of coal core No. 11579 was collected from coal seam 409/4, near to the D-6 gallery in the Zofiówka Coal Mine, Poland. The coal seam map with the location of the D-6 gallery was published by (Młynarczuk & Wierzbicki, 2009). This type of coal contains a significant quantity of macerals of the vitrinite group (over 70%) and a very small quantity of macerals of the liptinite group. Reflectance R_r for "Polish" coal was 1.13%.

TABLE 1

Localization and petrographic characterization of tested samples

Sample No.	**4312**	**5214**	**5216**	**11579**
Mine	**ČSM**	**Paskov**	**František**	**Zofiówka**
Borehole / Depth [m]	996 / 222,3	32347 / 95,2	F 3313 / 16,7	
Galery / Stationing [m]	—	—	—	D-6 /6,0
Stratigraphic horizon	Saddle Mbr.	Petřkovice Mbr.	Poruba Mbr.	Rudzkie Mbr.
Coal seam	5 05 + 504 CZ	047 CZ	420 CZ	409/4 PL
Reflectance of vitrinite R_r [%]	1,22	1,56	1,23	1,13
Maceral composition [%] * V/I/L/Min	50/44/5/1	75/21/0/4	85/8/5/2	71/22/4/3

* V – content of vitrinite macerals, I – content of inertinite macerals, L – content of liptinite macerals, Min – minerals content.

The second type of material used were briquettes made from coal dust. Full control over the course of the experiments is necessary to draw logically validated conclusions. One of the most important elements of such control is to ensure repeatability of the sample preparation. In the case of hard coal acquired directly from a coal seam, this requirement is very hard to meet. Most of these problems can be avoided by using homogenous coal briquettes of known and repeatable properties (Fig. 1). Properties of such briquettes can be easily modified by changing the pressing force. Coal briquettes were used as a "reference material" by the authors Kožušníková and Wierzbicki (2009).

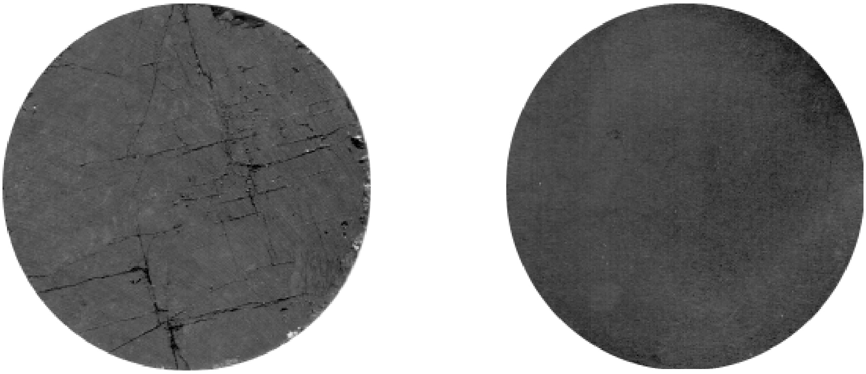
1A 1B

Fig. 1. Natural coal core (1A) and homogenous coal briquette (1B) (core and briquette diameter are 48 mm)

3. Preparation of the briquettes

The coal briquettes for the reference measurements were formed from coal taken from near to the D-6 gallery of the Zofiówka Coal Mine. The basic characterization of this coal is described in Section 2 – Tested Material. The coal sample was broken up and then ground by a ball mill. The grain class of < 0.2 mm was sieved and then averaged out. The density of coal was determined by the helium pycnometric method using an AccuPyc device. It amounted to $\rho_{He} = 1.365 \pm 0.004$ [g/cm^3]. Coal briquettes were formed by pressure. This method is described in detail by Wierzbicki (2003). A schema of the device used for preparing coal briquettes is presented in Figure 2.

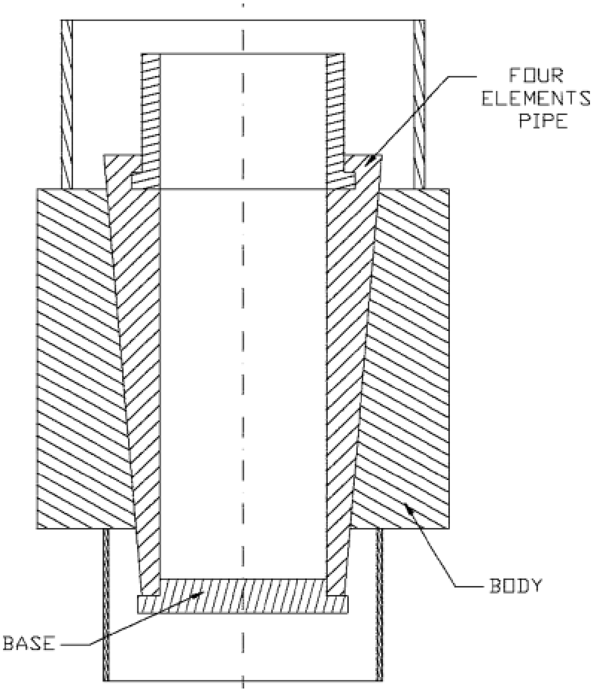

Fig. 2. Schematic of device used for preparing coal briquettes

Experience gained from creating briquettes (Wierzbicki, 2003) leads to the following assertions:

- During pressing, an axially symmetric stress distribution is formed in the briquette.
- The force that is present between neighbouring grains increases the durability of inter-grain bonds, which implies an increase in briquette durability. In other words, briquettes become denser.
- Knowing the relation between the briquette's average porosity and the pressing stress, it is possible to create repeatable briquettes of the desired porosity.

The helium density of the coal skeleton forms a basis for calculating the porosity ϕ – an important parameter of coal briquettetes. Briquette porosity was determined, based on the known bulk density of the briquette ρ_b and the density of coal skeleton ρ_{He}, from equation (1):

$$\phi = 100\left(1 - \frac{\rho_b}{\rho_{He}}\right) \tag{1}$$

The briquette volume was determined based on the geometric dimensions. The cylindrical test briquettes used for the permeability measurements had a length of 60 mm and a diameter of 48 mm, from which the cross-sectional area of specimen A is stated. Coal briquettes characteristic can be find in table 2.

TABLE 2

Characteristic of coal briquettes – helium density and total porosity

Briquette	**Helium density** ρ_{He} **[kg/m^3]**	**Bulk density** ρ_b **[kg/m^3]**	**Porosity [%]**
12625/2	1365	874	36.0
12625/3	1365	934	31.6
13027/B	1365	977	28.4
12625/7	1365	1016	25.6
13028/A	1365	1051	23.0
13029/A	1365	1098	19.6

4. Method of permeability measurement

The equipment for the permeability measurements consists of a KTK 100 triaxial cell from UNIPRESS (Poland) modified for gas passages. The confining pressure of oil ($\sigma_2 = \sigma_3$) is developed on the test specimen up to the value of 30 MPa. The source of axial stress (s_1) is a ZWICK 1494 mechanical press (Germany) with a maximum force of 600 kN, controlled by a computer. The method of measurement is based on the gradual increase in pressure of the oil in the triaxial cell. The induced confining pressure gradually increases from 5 MPa up to a maximum of 30 MPa with steps of 5 MPa. The axial pressure is set to the same value as the confining pressure so that, in the test specimen, a hydrostatic three-dimensional stress status is induced ($\sigma_1 \approx \sigma_2 = \sigma_3$). This hydrostatic pressure of 30 MPa corresponds to a depth in the rock massif of approximately 1000 m calculated from the general rock density.

The pressure of the gas medium is regulated from the gas pressure vessel by a control valve so that, during the whole period of the experiment, the pressure P_{up} is 0.5MPa. Nitrogen (dynamic viscosity $\mu = 1.75 \times 10^{-5}$ Pa · s) was applied as a gas medium for all experiments. This gas behaves as an inert medium for rocks and no adsorbtion for coal samples was observed during the short experiments (Konečný & Kožušníková, 2010). The gas passes through a capillary up to the cylindrical part and through a special screen that distributes the gas to the upper base of the rock specimen with cross-section area A. Gas with an atmospheric pressure P_{down} flows through the screen from the low base of the rock specimen to the output. At a selected hydrostatic pressure, the volume flow of nitrogen Q passed through specimen with hight L is measured and intrinsic permeability k [m^2] is calculated, according to Darcy's law, by Equation (2) (ASTM Standards, 1990; Konečný & Kožušníková, 1996, 2011).

$$k = \frac{2Q \cdot \mu \cdot L \cdot P_{down}}{A \cdot (P_{up}^2 - P_{down}^2)} \tag{2}$$

The specimen, screen and jaws are protected from oil penetration by the rubber packing. During this experiment, no briquettes or coal cores were broken. A schema of the test set-up is presented in Figure 3.

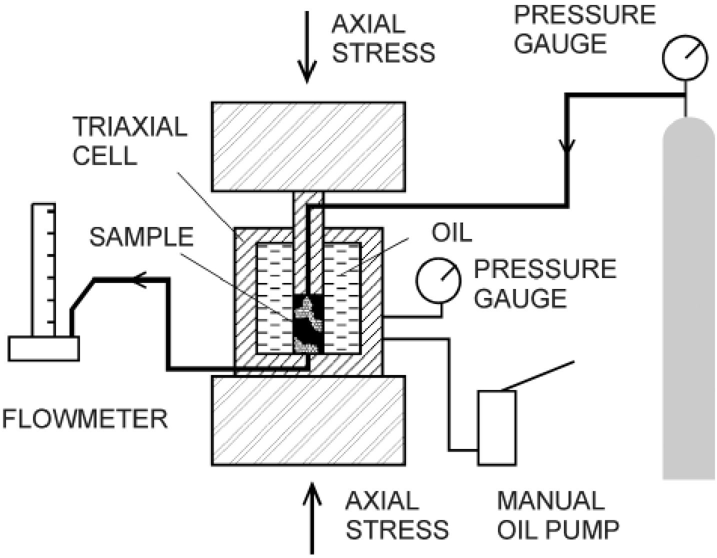

Fig. 3. Scheme of the testing set-up for permeability measurement

5. Results and discussion

The relationship between the permeability experimental results and confining pressure can be described by the empirical relation in equation 3 (Huy et al., 2010)

$$k_\sigma = k_0 \cdot e^{-B \cdot \sigma_3} \tag{3}$$

where k_0 is the theoretical initial permeability for an unloaded specimen and σ_3 is the confining pressure.

The initial permeability of the coal briquettes depends on their porosity. Increasing the porosity causes an increase in the initial permeability (Table 3).

TABLE 3

Initial permeability and coefficients of empirical relation (3)

Porosity [%]	**k_0 [m^2]**	**B [MPa^{-1}]**	**R^2**
36,0	2E-14	0,084	0,995
31,6	6E-15	0,074	0,994
28,4	5E-15	0,071	0,997
25,6	2E-15	0,049	0,992
23,0	1E-15	0,044	0,999
19,6	7E-16	0,040	0,971

Coefficient B is also influenced by the briquette's porosity. Points in the graphs in Figure 4 were fitted to an exponential curve of type $k = k_0 \cdot e^{-B\sigma}$. The correlation coefficients $R^2 > 0.97$ indicate that the fitted curves describe well the changes in permeability due to the changes in confining pressure. Value k_0 in the equation corresponds to the calculated value of the permeability

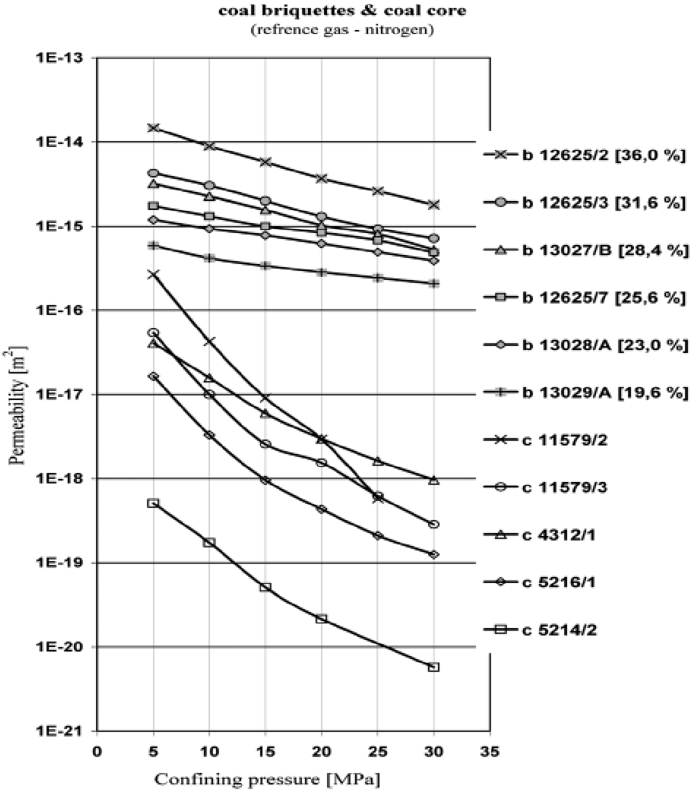

Fig. 4. Influence of confining pressure on the changes of nitrogen permeability of coal briquettes with various porosity (b) and coal cores (c)

of the material at zero confining pressure. This means that the kind of change in permeability due to the change in confining pressure is not affected by the type of coal. Coefficient *B* is obviously affected by the pressure used for preparation of the briquettes. The effect on the permeability of the pressure used for the preparation of the briquettes is evident from the graph in Figure 4. The coal briquette made at the lower pressure shows higher porosity and permeability. It is evident that the decrease in the permeability of the briquettes with the higher initial porosity due to the increase in confining pressure is more intensive.

The changes in permeability of the coal core samples are shown in Figure 4. The significant decrease in permeability is evident with the increase in confining pressure (Konečný & Kožušníková, 2011; Jasinge et al., 2010). A more intensive decrease in permeability during the increase in confining pressure in some specimens is caused by the presence of stress-sensitive cracks (see Fig. 1).

The total porosity of the coal cores of the USCB has a very wide range. It depends mainly on the presence of cracks and fissures in the coal. It ranges from 5% to 19% (Neset, 1973).

The measurements of gas permeability in the coal core samples confirms that coal core is more sensitive to confining pressure because the cracks and fissures in the coal core tend to close under triaxial stress.

6. Conclusion

The tested specimens – both coal cores and coal briquettes – show similar behaviour in the process of increasing the confining pressure. The decrease in permeability in the measured range of the confining pressures up to 30 MPa shows the differences for specimens of coal cores and coal briquettes. The permeability of coal briquettes decreases by up to one order compared to the three orders in coal cores. This phenomenon is caused by the presence of stress-sensitive cracks and fissures in the coal core specimens. The permeability variation in coal briquettes can be expressed by an exponential equation. This empirical relation is in good correspondence with the published results.

Coal cores behave in a different way. This different behaviour in comparison to coal briquettes is caused by the presence of cracks and fissures. These natural discontinuities affect the permeability of the "coal matrix" more than the porosity. The system of preparation of coal briquettes as a "reference material" eliminates the presence of discontinuities in comparison to the coal core.

The importance of measuring gas permeability changes due to the pressure changes in different values of gas permeability for specimens exposed to confining pressure and those not so exposed. The results are important for the qualification of the filtration behaviour of coal in stress conditions in the rock massif.

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