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Effect of compressive stresses on permeability of coal: Experimental and modeling estimates

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Abstract. Research findings on permeability of fractured coking fat coal from Tikhov Mine are presented. It is shown that rock pressure has considerable effect on coal permeability under various gas pressure gradients. In particular it is found that an increase in the triaxial compression from 1 to 8 MPa reduces coal permeability by 8–1 times if the gas pressure gradient is 0.67–1.34 MP/m and by 6.1–7 times if the higher gradient is equal to 2–3.3 MPa/m. Parameters of cleats and sizes of joints (blocks) in coal matrix are studied before and after loading of coal specimens. It is obtained that the size of the coal matrix blocks in the unloaded state is 530 μm at the width (opening) of cleats of 12.7 μm, which decreases by 1.8 times under the triaxial compression equal to 8 MPa. The measured parameters of cleats and coal matrix blocks are used to assess permeability of coal using theoretical models relating coal permeability with porosity or effective stress (compression) of coal. The comparison of the theoretical estimates and experimental studies of fractured coal shows that the measured permeability of coal under compression from 1 to 5 MPa agrees with the estimates by the permeability–porosity model. If the compression is higher than 5 MPa the estimates by different models coincide. It is found that the highest disagreement between the measured and calculated permeabilities takes place at the low gradient of gas pressure which is probably connected with the Kinkenberg effect.

1. Introduction

Permeability of coal is an important characteristic to be taken into account in underground mine planning, design and operation, in particular, in gas drainage. According to general views, methane flows in natural cleavage system [1–3]. The rate of gas flow depends on properties of cleats, namely, their number, width (opening), interconnectivity, length in the flow direction, etc. [4, 5]. The known theoretical models for coal permeability assessment are based on dependence of gas flow rate on either porosity or effective compression of rocks [6, 7].

This paper presents lab test results on permeability and parameters of cleats in fat coal in Tikhov Mine and analyzes the measured and calculated permeabilities using the known theoretical models [8–10].

2. Equipment

Gas permeability of coal was determined using a test facility designed in the Laboratory of Physical Methods of Impact on the Rock Mass at the Institute of Mining, SB RAS [11]. The facility provides the opportunity to study filtration of gas in cylindrical specimens of low-permeable rocks under separately adjustable axial and lateral pressures equal to 30 MPa. The facility set involves a measurement system for automatic long-term testing by a preset program.

Coal jointing analysis was carried out on instrumentation and software system Mineral S7, including optical microscope OLYMPUS BX51, video camera SIMAGIS 2P-3C, personal computer and specialized software. Additionally, ultraviolet radiation equipment composed of an upright frame platform with fixed LED UV emitters [12].

3. Preparation of specimens

The tests were carried out on coking fat coal sample at 200 m level in Tikhov Mine (Kuzbass). Permeability was tested in cylindrical specimens with diameter D = 30 mm and height L = 30–60 mm. For the cleavage analysis polished sections were made in a way so that their surfaces disclosed microstructure of coal in cross-section of the specimens. The polished sections were finished using abrasive fine diamond powder with particles less than 0.05 μm [13]. Before the tests the prepared specimens were saturated with luminophore in low vacuum. Application of such adsorptive substance on specimens provides the opportunity to find defects of internal volume. The capacity of luminophore EpoDye powder to dissolve at a ratio of 1:40 was used. Then, the specimens were drying at a room temperature in a dark place for 24 h. The cleavage tests involved 5 specimens. A detailed description of the specimen preparation procedure is given in [12].

4. Experimental procedure

The tests on coal permeability were carried out using nitrogen filtration in axial direction of cylindrical specimen under continuous pressure difference (ΔP) at the specimen faces. The pressure difference varied in the tests from 0.01 to 0.1 MPa at an increment of 0.01–0.02 MPa. Triaxial compression P was varied from 1 to 8 MP at a step of 2 MPa. A series of tests was performed for each value of P with different ΔP. The permeability was calculated using the procedure from [14].

Cleavage of coal was examined in a reflected light. After each loading cycle by the pressure P, coal microstructure was analyzed, including determination of the number and width (opening) of cleats, size of blocks in coal matrix and angle between the systems of cleats. The tests were carried out using 5X and 10X lens systems. For each cleat and coal matrix block not less than 100 measurements of width were taken along a cleat. Not less than 5 measurements of angles of cleats were made. The obtained data was processed statistically with determination of average values for the model analysis.

5. Discussion of results

The experimental relationship of the gas permeability coefficient and pressure difference ΔP under different compression P of coal specimens is demonstrated in Figure 1. Review of literature sources shows that the obtained values are typical of heavily jointed coal [15].

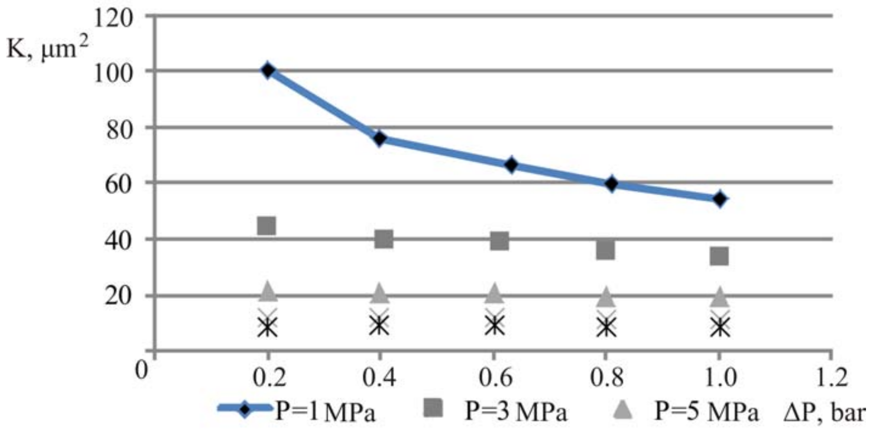

Figure 1. Gas permeability coefficient K_g, versus pressure difference ΔP of nitrogen in coal specimens under triaxial compression by P = 1, 3, 5, 7 and 8 MPa.

According to [16–18], bituminous coal structure is described by a system of cleats, including face cleats and butt cleats which can be perpendicular to each other and to the bedding plane (Figure 2). The similar structure was revealed in the specimens of fractured fat coal in the tests (Figure 3).

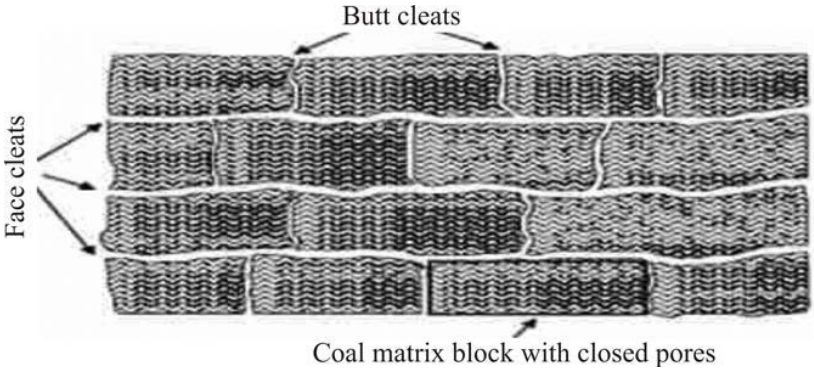

Figure 2. Sketch of typical structure of crevassed coal [19].

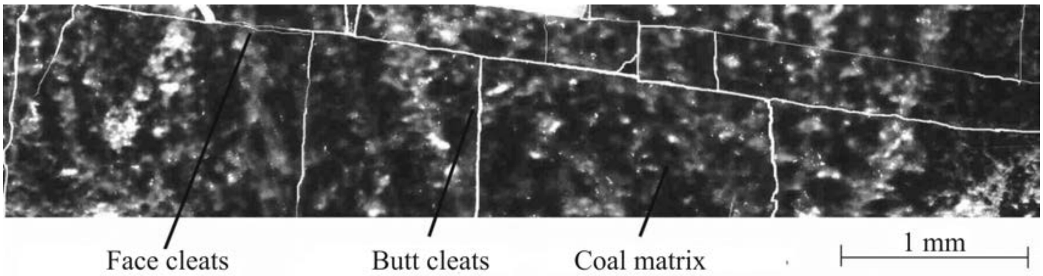

Figure 3. Cleavage in fat coal (level 200 m, Tikhov Mine): cleats are colored white.

Using the instrumentation and software system Mineral S7, the microscopic studies into parameters of cleats and coal matrix blocks were performed under atmospheric pressure (without load) before and after loading of a specimen in a test cell. The average size of blocks in the coal matrix was 530 μm, and the width (opening) of cleats was 12.7 μm. Average opening of cleats reduces by 1.8 times (from 12 to 6.5 μm) as the compression P is increased by 8 times (from 1 to 8 MPa). The average angle between both type cleats was 101°.

The obtained characteristics were used to calculate coal permeability by the Levine model [8]. The model estimates the change in the cleat opening under the influence of compression of rocks and shrinkage of matrix due to methane desorption by the formula

$$\frac{b_2}{a} = \frac{b_1}{a} + \frac{1-2\nu}{E}\left(P - P_0\right), \tag{1}$$

where a is the size of blocks in the coal matrix; b_1 is the initial width of cleats (under compression by P_0); b_2 is the final width of cleats (under compression by P); ν is Poisson's ratio (approx 0.3 for coal); E = 2500 MPa is the measured elasticity modulus of coal.

The permeability coefficient of coal, k, is found in terms of the obtained width of cleat and average size of blocks in the coal matrix from the formula

$$k = \frac{1.013 \cdot 10^9 \cdot b_2^3}{12 \cdot a}. \tag{2}$$

According to [8], the change in the size of blocks owing to the coal matrix compressibility can be neglected (i.e. a = const). Furthermore, we disregarded influence of gas desorption on opening of cleats, which is insignificant in nitrogen.

In the other known model [9, 10], the effect of compression on permeability of coal is assessed by the formula

$$k = k_0 \cdot e^{-3C_f \cdot (P-P_0)}, \tag{3}$$

where k_0 is the permeability coefficient under initial compression P_0, μm^2; C_f is the compressibility of cleats, MPa^{-1}; P is the compression of coal, MPa. Compressibility of cleats was assessed using he procedure described in [20]. The measured value of the initial coal permeability k_0 at the atmospheric pressure made 69.9 μm^2 (mD).

The relationship of the measured permeability coefficients and triaxial compression P = 1–8 MPa in the specimens of fat coal is depicted in Figure 4. It is found that gas permeability lowers with increasing P, and the value of the reduction is higher for the smaller gradients of the gas pressure ΔP/L. For instance, at the pressure difference ΔP = 0.02–0.04 MPa (ΔP/L = 0.67–1.34 MPa/m), under the increase in P from 1 to 8 MPa, the permeability drops by 8–11 times, while at the pressure difference ΔP = 0.06–0.1 MPPa (gas pressure gradient 2–3.3 MPa/m), the drop in the permeability makes 6.1–7 times. Alongside the experimental data, Figure 4 shows the permeability coefficients calculated by the formulas (1), (2) of the model [8] (dashed line) and formula (3) of the model [10] (solid line). The statistical processing of the measurements and comparison with the calculated results yields that under the compression P = 1–5 MPa, the Levine model estimate is closer to the measurements [8]. Under the pressure P more than 5 MPa, the calculated results of both models are identical. The most essential disagreement between the experiment and calculation is observed at small gradient of gas pressure (at ΔP = 0.2 MPa). We assume that this is connected with the known phenomenon of gas slippage at the grain interfaces (Klinkenberg effect) promoting an increase in gas permeability of rocks under low reservoir pressure [21].

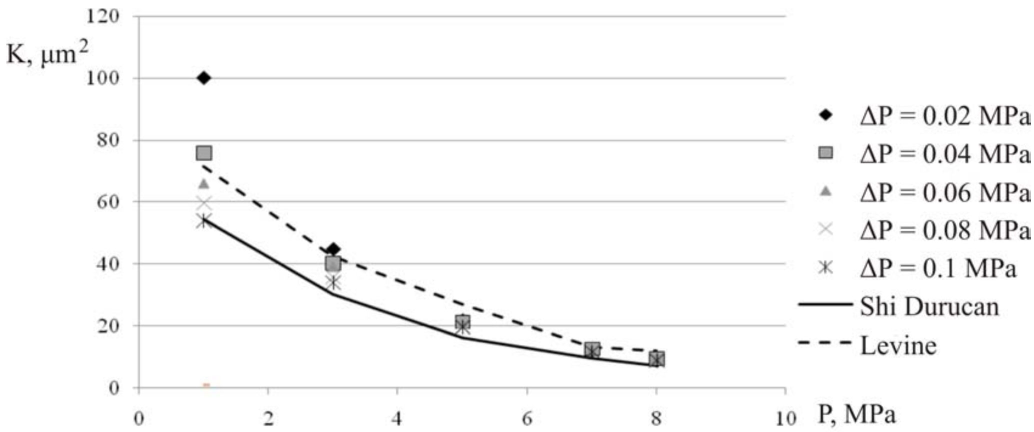

Figure 4. Relationship of gas permeability coefficient K_g and pressure P of coal: points—experiment; solid line—model [9, 10]; dashed line—model [8].

6. Conclusion

Permeability of fractured fat coking coal under increasing triaxial compression to 8 MPa drops from 69.9 μm^2 by a factor of 6–11. This drop depends on the pressure gradient of gas and intensifies as it lowers. For instance, permeability drops by 8–11 times if the gas pressure gradient is 0.67–1.34 MPa/m and by6.1–7 times at the gas pressure gradient is 2–3.3 MPa/m.

The average opening of cleats in the test unloaded fat coal specimens is 12.7 μm, the size of blocks in the coal matrix is 530 μm. These parameters can be used to assess permeability of actual coal seam by the Levine model [8] under rock pressure of 2–3 MPa and more. Under lesser compression and smaller gas pressure gradients (0.67 MPa/m and lower) as well as the average reservoir pressure, the theoretical calculations yield underestimated values of gas permeability in fractured coal (by 30% and more).

The obtained results can be used in prediction of gas permeability in fractured coal under compressive stresses conformable with reservoir conditions.

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