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Effect of compressive stresses on permeability of coal with fracture filled with lightweight proppant

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Abstract. The paper presents laboratory testing results on effect of hydraulic fracturing on permeability of coal with and without wedging of created fractures by proppant. The tests were carried out with hollow aluminosilicate microspheres ASPM-500 without and with additional polymeric thermoreactive coating, specimens of dense long flame (grade D) coal with permeability of less than $3 \cdot 10^{-3}$ μm^2 and fractured fat coking coal (grade ZH) with permeability over $60 \cdot 10^{-3}$ μm^2. It is found that creation of fractures with and without propping considerably improves gas permeability of dense coal with weakly developed natural jointing. Created fractures are less effective in highly jointed highly permeable coal. It is experimentally proved that filling of created fractures with small opening of 0.4 mm with lightweight proppant under uniform compression of 1–5 MPa improves permeability of dense coal by 7–19.5 times. In jointed coal, application of lightweight proppant under the same conditions improves permeability less considerably—by 1.2–2.6 times. It is revealed that efficiency gas drainage in coal by hydraulic fractures without propping lowers as compressive stresses decrease. Reduction in permeability of coal with propped fracture under growing compression is probably connected with redistribution and compaction of proppant particles in the fracture. The obtained results show that application of lightweight propping materials is a promising way of advance in the technology of hydraulic fracturing for stimulation of coalbed methane drainage. The long-range research, in the authors' opinion, should be focused on the development of lightweight proppants with improved strength characteristics.

1. Introduction

Gas drainage in coal seam under higher confining pressure is difficult due to low permeability of coal—not higher than 10^{-4}—$5 \cdot 10^{-3}$μm^2 as a rule [1]. For methane drainage at admissible rate and recovery, a dense grid of wells has a spacing of 3–10 m. The number of wells is only possible to be reduced by means of increasing the well radius. An efficient approach to this problem's solution is creation of many drainage channels in wells by hydraulic fracturing [2].

Analysis of the hydraulic fracturing experience in coal seams shows that productivity of drainage wells can be improved using arching materials (proppants). Numerous drainage channels filled with sand proppant (30/60 mesh) with opening of 3–4 mm and radius to a few meters, at a spacing of 4–6 m from each other, improve drainage borehole productivity by 5 times in coal seams with permeability of 0.02–0.03 μm and to 180 times in less permeable coal seams for several months [4]. At the same time, traditional proppant materials used for hydraulic fracturing of coal, such as quartz sand, ceramic spheres, early deposit in drainage holes and fractures. Combating this phenomenon with highly viscous fluids and/or high pumping velocity upvalues greatly hydraulic fracturing implementation, which results in preference of density drainage drilling layout [6, 7]. An admissible solution to this problem aimed to cut down meterage drilled is the use of lightweight proppants having similar density as water-based fracturing fluids. Such proppants are readily transferred in holes for a long time and well spread along the created fractures [7, 8]. However, they are soft and can be broken under closure of fracture edges under the action of rock pressure.

This article presents experimental research data on influence exerted by aluminosilicate microspheres ASPM-500 and lightweight proppant based on hollow aluminosilicate microspheres ASPM-500 with additional polymeric thermosetting envelope on permeability of coal under uniform compression. The comparative analysis of measured and calculated permeabilities from the known model of the effect of stresses and sorbing gas flow on evolution of permeability of coal filled mono-layered proppant is given [5].

2. Experimental research

Gas permeability of coal was determined on an installation designed at the Laboratory of Physical Methods of Impact on the Rock Mass at the Institute of Mining, SB RAS [9]. The installation is meant for determining gas-permeability of rocks in a testing cell with adjustable axial and lateral compression of cylindrical samples. The installation includes measurement system for automatic long-term investigation of rock permeability by preset program. Specification of the installation is given in [9].

Examination of the jointed coal structure and proppant grains with thermoreactive coating was carried out on the instrumentation and program system Mineral S7, including optical microscope OLYMPUS BX51, video camera SIMAGIS 2P-3C, personal computer and specialized software.

2.1. Samples

The tests were carried out on grade D coal (long flame) from the Karakan coal deposit (Permyakov open pit mine, Kuznetsk Coal Basin) and grade ZH coking coall (fat) from Tikhov Mine (Kuznetsk Coal Basin).

Two cylindrical specimens of 3 m diameter and 3 and 6 cm lengths were manufactured. Before the filtration tests were carried out, jointing of the specimens had been examined on two specimens of each coal grade. The preparation procedure of specimens is described in detail in [10, 11].

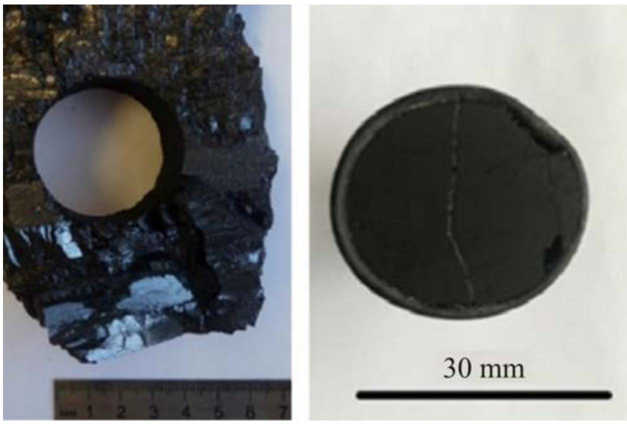

Figure 1. Coking coal grade ZH with a cutout after manufacture of cylindrical specimen (left) and long-flame (grade D) coal specimen with fracture filled with lightweight proppant (right).

In the cylindrical specimens, through axial fractures were made and, then, filled with proppants (Figure 1). Average opening of propped fractures under atmospheric pressure was 0.4 mm. In the tests of coal grade D, the proppant was a hollow aluminosilicate microsphere ASPM-500 (Figure 2a). Later on, the aluminosilicate microsphere were covered with thermoreactive coating and used as the proppant in the filtration tests of coking coal grade ZH (Figure 2b). The thermoreactive coating made of epoxy resin with magnesium particles and phenol-formaldehyde resin improves the strength of proppant, ensures cohesions of the sphere is the drainage channel and prevents their outflow to the drainage borehole [12]. Using the solid microstructure analyzer SIAMS Mineral S7, the size and shape of the main proppant fraction were determined. Average diameter of aluminosilicate microsphere was 140 μm, around 70% of particles had roundness above 0.8. Average diameter of the proppant grains with the polymeric coating was 400 μm, and their roundness was 0.65–0.7.

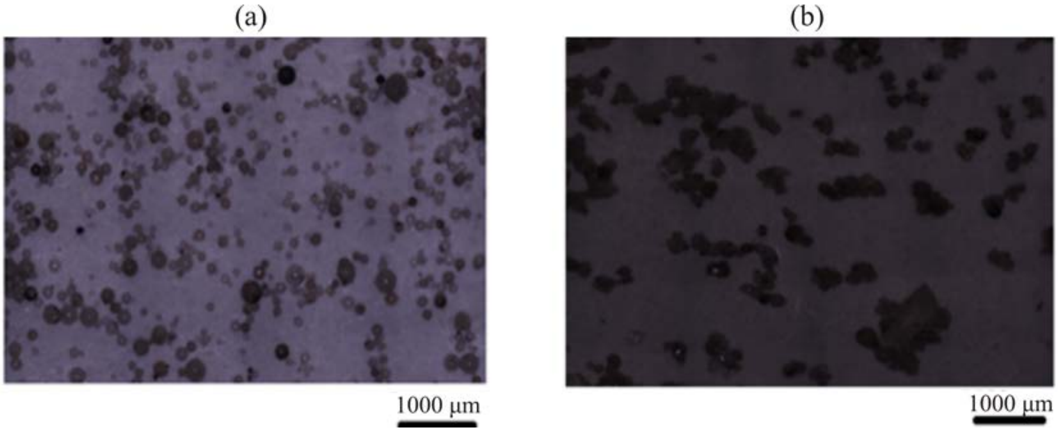

Figure 2. Lightweight proppants for tests: (a) hollow aluminosilicate microspheres ASPM-500; (b) microspheres ASPM-500 with polymeric coating.

3. Experimentation and data processing
Before the filtration tests, jointing of coal was examined in a reflected light. The microstructure analysis included determination of a number and width (opening) of cracks, size of blocks in coal matrix and angle between joint sets. For each crack and coal matrix block, not less than 100 measurements of crack width were taken along the crack strike. Not less than 5 measurements of angles between cracks were taken. The obtained data were statistically processed and averaged.

Coal gas permeability was tested using nitrogen flow in axial direction at constant pressure difference ΔP between the specimen faces and varied compression P.

At the first stage, permeability was tested without simulated hydrofracture. The uniform compression P was varied from 1 to 5 MPa at an increment of 1 MPa for long-flame coal and from 1 to 8 MPa at an increment of 2 MPa for fat coal. At each value of P, a series of tests was carried out at different ΔP from 0.01 to 0.1 MPa at an increment of 0.01–0.02 MPa. At the second stage, permeability of long-flame coal with a through crack without proppant was tested. At the third stage, the tests of permeability of coal with fracture filled with lightweight proppant were performed. In the long-flame coal tests, hollow aluminosilicate miscrosphere ASPM-500 were used; the tests of the fat coal were conducted with the ASPM-500 microsphere covered with polymeric coating. Proppant was uniformly spread on the fracture surface, the specimen was placed in the rubber cut-type seal, and a series of tests was implemented at P and ΔP specified above. For each value of ΔP, at least three experiments were carried out.

Gas permeability factor of specimens before and after proppant addition was calculated from the formula for linear gas flow and stationary filtration process [13]:

$$K_g = \frac{2 \cdot 10^4 V \mu_a P_3}{tS} L \frac{1}{P_1^2 - P_3^2}, \quad (1)$$

where K_g is the gas permeability factor, 10^{-3} μm^2·(mD); $P_1 = P_3 + \Delta P$ is the pressure at inlet *1* of the test cell (Figure 3), 10^{-1} MPa (bar); P_3 is the pressure at outlet *3* of the test cell (atmospheric),

10^{-1} MPa (bar); V is the volume of gas flow through the specimen under P_3, cm^3; μ_a is nitrogen viscosity, mPa·s (sP); S is the cross-section area of specimens, cm^2; L is the specimen length, cm; t is the time of gas flow through specimen, s [5]. For ach test series at a certain ΔP, the average gas permeability factor was calculated ($K_g av$).

4. Discussion of the results

According to the common knowledge, coalbed methane flows in natural cracks [14–16]. Thus, coal permeability directly depends on natural crack parameters. This is confirmed by the experimental research findings [16]. The microscopic analysis of cracks and blocks in coal matrix under atmospheric pressure shows that fat coking coal (ZH) has a typical jointing structure described in [14–16]. The average size of blocks is 530 μm, the width (opening) of cracks is 12.7 μm. Average angle between both type joints is 101°. The structure of long-flame coal specimens in the transverse cross-section to the cylindrical specimen axis is characterized by a set of natural joints 47 μm wide at the size of blocks of 4350 μm.

The first series of filtration tests shows that permeability of coal speciemsn D and ZH without crated fracture depends on uniform compression. It is found that permeability of denser D coal under compression increase by 5 times reduces on average by 3.1 times (from $2.8 \cdot 10^{-3}$ μ^2 at P = 1 MPa to $0.9 \cdot 10^{-3}$ μm^2 at P = 5 MPa). Permeability fat coking coal (ZH) under the increase in compression by 8 times reduces on average by 6.7 times (from $60 \cdot 10^{-3}$ μm^2 at P = 1 MPa to $9 \cdot 10^{-3}$ μm^2 at P = 8 MPa).

In the second experimental series, permeability of long-flam coal (D) with fracture without proppant was tested as a function of uniform compression P. The results are depicted in Figure 3. It is found that permeability drops on average by 17.6 times as compression is increased 5 times from 1 to 5 MPa. This implies low efficiency of gas drainage using created fractures without propping.

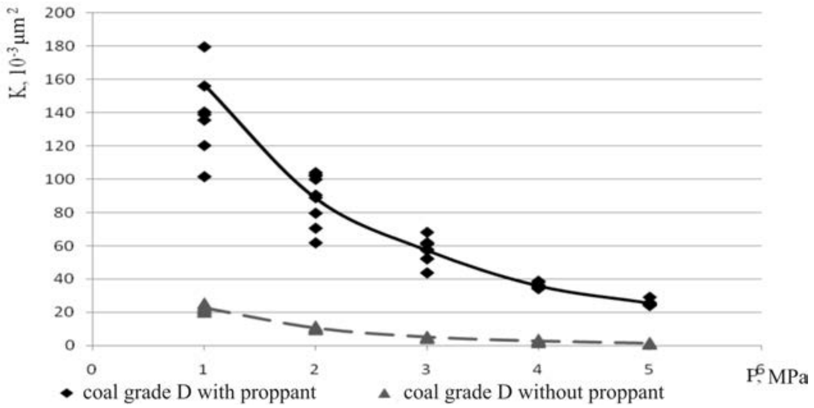

Figure 3. Gas permeability factor K in long-flame coal (grade D) with fracture without and with proppant (hollow aluminosilicate microspheres ASPM-500) versus compression P. Solid curve is plotted by averaged values of K for different pressure differences ΔP in specimen with proppant; dashed curve is plotted by average K for different ΔP in specimen without proppant.

In the third test series, we assessed influence of compression P on permeability of coal grades D and ZH with a through fracture filled with lightweight proppant. In D coal the fracture was filled with hollow aluminosilicate microspheres ASPM-500. Initial opening of the fracture (prior to compression) was 0.4 mm. It is found that permeability of coal grade D lowers on average by 6.2 times as the compression P is increased by 5 times from 1 to 5 MPa (Figure 3). The most probable causes of the permeability decrease are redistribution of proppant grains in the fracture (compaction of proppant), partial destruction and indentation of grains in coal under compression.

In the specimen of fat coking coal grade ZH, the fracture was propped using aluminosilicate microspheres ASPM-500 with polymeric coating. Initial opening of the fracture was 0.4 mm. the obtained results are demonstrated in Figure 4. It is found that coal grade ZH permeability decreases by 1.6–2 times as P is increased from 3 to 8 MPa. Thus, polymeric coating improves operating abilities of hollow aluminosilicate microspheres.

Permeability of coal with fracture filled with proppant in in-seam conditions was assessed using the known theoretical model [5]. The model describes influence of proppant indentation in the created fracture walls under the action of compressive stress, as well as effect of gas flow on opening and permeability of cracks in coal. In the model, fracture is filled with monolayered proppant. In the calculations, we disregard influence of sorption capacity of coal on fracture opening as for nitrogen the sorption effect is insignificant. According to [5] permeability is calculated from the expression:

$$k = k_0 \left(1 - \frac{R(1-\sqrt{1-\sigma/\pi C})}{b_0} \right)^3, \tag{2}$$

where k is the permeability factor, 10^{-3} μm^2; k_0 is initial permeability, 10^{-3} μm^2; R is the radius of proppant grains, mm; σ is the effective stress, MPa; $b_0 = 2R$ is the initial opening of fracture, mm; C is the cohesive strength of coal, MPa.

The modeling assumed some initial parameters. Initial permeability fits its value under under uniform compression P = 3 MPa and equals 42 10^{-3} μm^2. The proppant grain radius is the average radius of not less than 200 particles after microscopic analysis. The initial fracture opening b_0 is assumed to equal 2R, or 0.4 mm. The cohesive strength value C = 7 MPa is taken from literature [17].

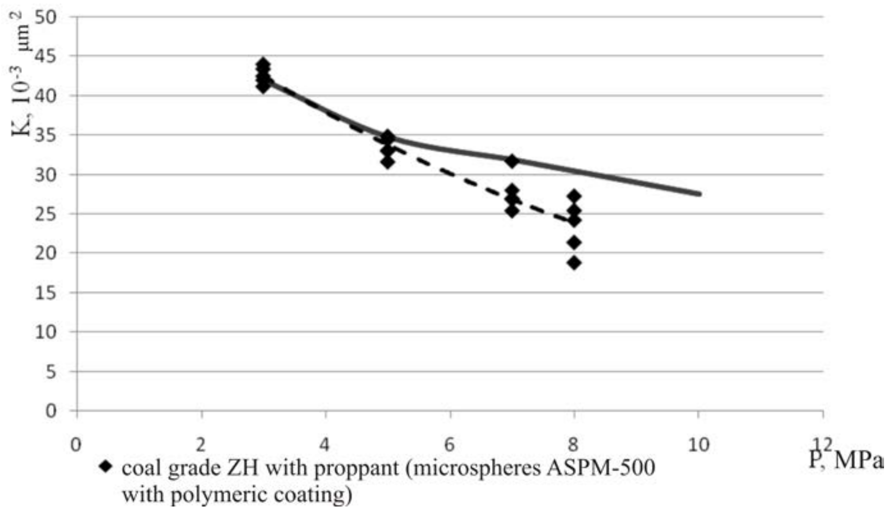

Figure 4. Gas permeability factor K in fat coal (grade ZH) with fracture filled with proppant (hollow aluminosilicate microspheres ASPM-500 with polymeric coating) versus compression P. Dashed curve is plotted by average values of K for various pressure differences ΔP. Solid curve is calculated using the model by Kumar, 2015.

The obtained results are shown in Figure 4. It is found that as the compression is increased, the disagreement of the experimental and calculated data grows. When P < 5 MPa the experiment and calculation curves coincide, while when P > 5 MPa they move apart, and the difference increases with higher compression. Thus, under compression less than 5 MPa, reduction in fracture opening and, consequently in permeability, depends, first of all, on indentation of proppant grains in the fracture walls. Considering strength characteristics of proppant (crushing strength limit 15–20 MPa), it is possible to conclude that the main cause of the disagreement between the experimental and theoretical data under compression higher than 5 MPa is redistribution and compaction of proppant grains.

The implemented research proves that lightweight proppants used to wedge created fractures improves permeability of coal, especially with low initial permeability and weaker jointing. In any case, efficiency of proppants grows under higher compression.

It is found that hydraulic fractures improve permeability of dense coal grade D by 2–8 times under increase in compression by 5 times. Wedging of fractures 0.4 mm initially wide by lightweight proppant improves permeability of coal on average by 7–8.5 times under compression of 1–2 MPa, by 11–14 times under P = 3–4 MPa and by 19.5 under P = 5 MPa. For fractured fat coking coal (grade ZH) under the same conditions, permeability is improved from 1.2 times under P = 3 MPa to 2.6 times under P = 8 MPa. Lower efficiency of hydraulic fracturing in fractured coal is governed by higher initial permeability of coal (more than 60 μm^2) due to developed system of natural fractures.

5. Conclusion

It has been found that hydraulic fracturing with and without propping considerably improves gas permeability of coal ($<3\cdot10^{-3}$ μm^2) with weakly developed natural jointing. Effect of created fractures on permeability of heavily jointed highly permeable coal ($>60\cdot10^{-3}$ μm^2) is less than in denser coal. Wedging of 0.4 mm wide fractures by lightweight proppant in denser coal without created fractures improves permeability by 7–8.5 times under compression P = 1–2 MPa, by 11–14 times under P = 3–4 MPa and by 19.5 times under P = 5 MPa. For fractured fat coking coal (grade ZH) permeability is improved by 1.2 times under P = 3 MP and by 2.6 times under P = 8 MPa under the same conditions.

It has been proved that efficiency of gas drainage in coal with hydraulic fractures unfilled with proppant reduces with increasing compressive stress. Reduction in coal permeability with propped fractures under increasing compression is probably connected with redistribution and compaction of proppant particles in fractures.

The obtained results demonstrate that the application of lightweight proppants is a promising way of advance in the technology of hydraulic fracturing for coalbed methane drainage. The long-range research, in the authors' opinion, should be focused on development of light-weight proppants with improved strength characteristics. Solution of this problem will ensure improved permeability of created fractures in coal beds, at pumping of working fluid and propping materials using small-capacity equipment, which is of concern for operation in the condition of a mine.

Acknowledgements

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