Effect of the proppant on fracture compressibility in coal seam

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Abstract. The paper discusses enhancement of gas drainage well productivity in coal seams using the hydraulic fracturing technology. Filling of a fracture with proppant provides a long-term increase in the gas drainage well performance. The results of the laboratory experiments to determine coal permeability under various stress conditions show that proppants significantly reduce fracture compressibility and the propped fracture becomes less sensitive to stress variations.

1. Introduction

Pre-mine gas drainage is a component of underground mining of gas-bearing coal seams. Gas content of coal increases with deeper level mining, and gas drainage efficiency gains in the practical importance. Hydraulic fracturing creates additional fluid channels from coal to well, which improves flow dynamics [1, 2]. Longer-term deliverability of gas wells can be achieved by propping created fractures [3, 4]. The lab-scale tests data and the field studies of coal permeability enhancement with proppants can be found in [2, 5–8].

It is commonly assumed that coal seams have a discontinuous structure defined by joints and blocks, and methane flows in natural cracks [9, 10]. The fracture flow capacity in terms of as depends on the properties of fractures, their number, width (opening), connectivity, length in the line of flow, etc. as a rule, coal permeability estimates neglect permeability and compressibility of blocks separated by joints [11, 12]. A coal seam experiences internal stresses induced by fluids in pores and external stresses due to lithostatic pressure. Fluid outflow from pores induces the change in the internal stress in the seam, and the effective stress grows as a result with the change in porosity, in total volume of rock, etc. Compressibility of pores in rocks characterizes the relative change in porosity per unit pressure change [13]. Coal porosity is mainly governed by coal jointing, and fracture compressibility in coal can be assessed using the procedure proposed in [14, 15].

This paper presents the laboratory studies into the influence of a light proppant on the fracture compressibility in coal. The tests were carried out with varied compression (from 0.1 to 5 MPa) and pore gas pressure in accordance with the procedure from [15].

2. Permeability tests and results

Permeability tests were implemented on a special installation designed at the Institute of Mining, SB RAS and intended for compression tests of rock samples. The detailed description and specifications of the installation are given in [16].
The tests were carried out on cylindrical specimens with diameter and length of 3 cm made of long-flame coal of the Karakan field. Before testing, fracture porosity of coal was studied. To that end, polished sections to show surface microstructure of coal were made. The specimens were saturated with luminophore in low vacuum to reveal volumetric defects. The coal microstructure was analyzed on three specimens in reflected light on solid microstructure analyzer SIAMS Mineral S7.

The cylindrical specimens were fractured along a generatrix, which formed through cracks in the plane of the specimen axis. The surface of the specimens was polished using diamond paste made of abrasive particles 20, 10, 5 and 1 μm. Figure 1a shows the treated faces of the crack. The created cracks were filled with proppant (Figure 1b) and the specimens were placed in the test cell. The average opening of the propped cracks under the atmospheric pressure made 0.4 mm. The proppant was hollow aluminosilicate microspheres ASPM-500 with bulk density of 0.6–0.7 g/cm², main fraction size of 140 μm (around of 70%) and roundness more than 0.8 (Figure 2).

**Figure 1.** Faces of through crack along the axis of cylindrical specimen of long-flame coal (a) with and (b) without proppant.

Before permeability tests, the fracture porosity of coal was studied in reflected light. The microstructure analyses determined the number and width (opening) of fractures, sizes of blocks, and angles of the joint sets. For each joint and block, not less than 100 measurements of fracture width were taken along the fracture length. The data were statistically processed and the average values were calculated.

In the coal permeability tests, nitrogen flow was maintained in the axial direction, under constant differential pressure $\Delta P$ and varied compression pressure $P$. At the first step, coal permeability was tested without a through crack. The uniform axial and lateral compression $P$ of a long-flame coal specimen was changed from 1 to 5 MPa at a pitch of 1 MPa. For each value of $P$, a series of tests was implemented at the varied differential pressure $\Delta P$ from 0.01 to 0.1 MPa at a pitch of 0.01–0.02 MPa. The experimental temperature was ranged as 22–26 °C.
At the second and third steps, permeability of long-flame coal was tested in the specimens with a through crack without and with a proppant represented by microspheres ASPM-500. The proppant was uniformly applied to the face of the crack, then the halves of the split cylindrical specimen were connected to each other, and the suchwise obtained specimen was placed in a rubber gland and, then, in a test cell and were subjected to compression by \( P = 1 \text{–} 5 \text{ MPa} \) at a pitch of 1 MPa and at \( \Delta P = 0.01 \text{–} 0.1 \text{ MPa} \). At each value of \( \Delta P \), not less than three tests were performed at the temperature 21–25 °C.

The fracture permeability without the proppant and with it was calculated from the expression [11, 17]:

\[
K_f = \frac{10^5 h W^3}{12A},
\]

where \( K_f \) is the fracture permeability, \( \mu m^2 \); \( h \) is the fracture height (perpendicular to the pressure gradient), cm; \( W \) is the fracture width, cm; \( A \) is the area of the fracture in the transverse section of the flow, cm².

The permeability of a through axial crack in the cylindrical specimen is given by:

\[
K_f = \frac{(K - K_s) \pi R}{2W} + K,
\]

where \( K, K_s \) are the permeabilities of the specimen with and without a through crack, respectively, \( \mu m^2 \); \( R \) is the radius of the specimen, cm; \( W \) is the opening of the fracture, cm.

The fracture permeability without and with the proppant was found from expressions (1) and (2) for each value of \( P \). The compressibility of the fracture without and with the proppant was estimated using the procedure from [14, 15]:

\[
K_f = K_{f0} e^{-3C_f(\sigma - \sigma_0)},
\]

where \( K_{f0} \) is the initial permeability of the fracture, \( \mu m^2 \); \( C_f \) is the fracture compressibility, \( MPa^{-1} \); \( \sigma_0 \) is the initial effective stress, MPa; \( \sigma \) is the effective stress, MPa.

The test data were compared with the results on compressibility of natural fractures in coal. The gas permeability of a whole specimen without a through crack was calculated using the Darcy law for linear gas flow and for stationary seepage [18]. The compressibility of natural fractures was assessed using formula (3).

The microscopic analysis of joints and blocks in the transverse cross-section relative to the axis of of the cylindrical long-flame coal specimens reveals the system of natural cracks having average width of 47 μm and the average block size of 4350 μm. The permeability tests of long-flame coal specimens without a tensile fracture related the permeability with the uniform compression. The permeability is \( 2.8 \times 10^{-3} \mu m^2 \) at \( P = 1 \text{ MPa} \) and is \( 0.9 \times 10^{-3} \mu m^2 \) at \( P = 5 \text{ MPa} \), the average compressibility of natural cracks is 0.094, and the compressibility of a through fracture without the proppant is 0.0048 MPa⁻¹ (see the Table 1 and Figure 3). Addition of hollow alumosilicate microspheres ASPM 500 greatly reduces the fracture compressibility to \( K_f = 0.00069 \text{ MPa}^{-1} \) (Table 1 and Figure 3).

| \( P \), MPa | \( K_f, \text{ MPa}^{-1} \) |
|-------------|-----------------|
|             | Coal without fracture | Coal with created fracture |
|             | without proppant | with proppant |
| 1           | 0.093           | 0.007       | 0.00071 |
| 2           | 0.094           | 0.0059     | 0.00086 |
| 3           | 0.094           | 0.0046     | 0.00072 |
| 4           | 0.095           | 0.0036     | 0.00060 |
| 5           | 0.094           | 0.003      | 0.00053 |

Table 1. Fracture compressibility factor \( K_f \) in coal under different compression pressure \( P \) and gas pressure \( \Delta P = 0.1 \text{ MPa} \).
Figure 3. Ratio $a$ of average compressibility factors of natural cracks (C1), created fracture without proppant (C2) and with proppant (C3) versus uniform compression $P$.

3. Conclusions
The tests of the Karakan long-flame coal specimens from Kuzbass have shown that the use of proppants in the created fractures allows considerable increase in coal permeability and has a great effect on the compressibility of the created fracture. The fracture compressibility with the proppant, given initial opening of 0.4 mm and uniform compressive loads of 1–5 MPa, decreases 5–9 times as compared with the created fracture without proppant and by 2 orders of magnitude as compared with natural cracks in coal. Permeability and compressibility of fractures with the proppant are less sensitive to variation in stresses.

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