Permeability of Coking Coals and Patterns of Its Change in Leninsky Area, Kuznetsk Coal Basin, Russia

Tatiana Shilova * and Sergey Serdyukov

Chinakal Institute of Mining, Siberian Branch of Russian Academy of Sciences, Krasnyi ave. 54, Novosibirsk 630091, Russia; mailigd@misd.ru
* Correspondence: shilovatanya@yandex.ru

Abstract: A prediction of the permeability of gas-bearing coking coals in the Leninsky area, Kuznetsk coal basin (Kuzbass), which is promising for the production of coal methane, was performed. The results of laboratory studies of coal permeability and cleat compressibility under hydrostatic stress conditions are presented. As the confining pressure increased by 8 times (from 1 MPa to 8 MPa), the coal permeability perpendicular to the butt cleat direction decreased by 6.7 times (from 60 mD to 9 mD). The coal cleat compressibility was 0.085 MPa$^{-1}$. On the basis of the results of filtration tests and microstructural analysis of the coking coals, we provide the estimation of the permeability anisotropy along the bedding planes (perpendicular to the face and butt cleat directions). The predicted dependences of gas-bearing coking coal permeability perpendicular to the butt and face cleat directions on depth and on features of coal seam bedding were determined under uniaxial strain conditions. It was found that in the coking coal depth intervals, as the depth increased, their permeability decreased by 61–82%. The obtained results can be used to select facilities and to design industrial works for the extraction of coal methane in the region.

Keywords: coal; permeability; cleats; anisotropy; stress; gas drainage

1. Introduction

The recent intensification of mining and usage of coal resources is associated with an increase in mining depths. A coal seam is a CBM reservoir. Generally, the gas content increases with depth, while the rock permeability decreases. These features can produce dynamic disasters, such as gas outbursts and explosions, and stop mining operations in underground mines [1–3]. Simultaneously, CBM is a valuable energy resource that is used worldwide, especially in countries such as the USA, Australia, and China. Despite the large CBM potential of Russian coal basins, there is practically no production of methane on an industrial scale. Gas drainage of coal seams is an essential technique that is used both to prevent gas dynamic disasters in mines and to produce CBM for later utilization. Coal permeability should be considered in gas drainage design and performance assessment, as it is an important parameter that affects gas filtration in rocks and thus CBM production [1,4–7]. Modeling coal seam permeability is necessary to design gas drainage systems and to optimally extract CBM to the surface via wells [8].

Coal acts as a naturally fractured reservoir and exhibits two sets of natural fractures (cleats) caused by the alteration of the coal composition from its initial state. The dominant and secondary fracture systems are termed face and butt cleats, respectively. Additionally, a system of natural fractures forms along bedding planes, but most of these fractures are not very well developed due to the weight of the overlying rocks [9,10]. The heterogeneity of the coal seam structure causes permeability anisotropy, which has been confirmed by numerous laboratory studies [1,9,11–13]. Typically, within engineering accuracy, the coal permeability variations within mined seams are accepted as negligible. However, this variation can reduce the efficiency of designed gas drainage systems, which complicates...
the mining of coal seams and increases the risks of gas hazards. Accounting for permeability, anisotropy allows one to optimize the location of gas drainage wells, improve hydraulic fracturing for CBM extraction, etc. [9,14]. There are theoretical models linking heterogeneous coal permeability and the anisotropy of rock mechanical properties with structural characteristics [15–17]. A microstructural analysis can be realized on small-diameter coal cores sampled from a single well. Such studies allow the evaluation of the required parameters in unloaded and loaded rocks [13].

In situ coal permeability depends on the local stress conditions. The permeability of a coal seam varies due to the increase in the effective stress with depth; the increase in effective stress caused by CBM extraction; and the decrease in pore pressure, which results in the coal matrix shrinkage effect [2,18–20]. Numerous theoretical and empirical models are available to predict coal permeability. A review of the known models is presented by Pan et al., (2012) [6]. The models, which consider the uniaxial strain of coal seams, are used to describe the variation in permeability with depth. The permeability is assumed to be dependent on either the rock mean stress or compression stress across cleats. The description that uses uniaxial strain conditions is a simplified description, but it can be sufficiently accurate, as in situ coal deposits are confined laterally. The uniaxial strain coal permeability models are reasonable at the scale of coal areas and basins [9]. A reference coal permeability and cleat compressibility are initial model parameters and are determined by the results of laboratory filtration experiments under hydrostatic stress conditions. Theoretically modeled dependencies are widely used to approximate the obtained experimental data [20,21]. The Shi and Durucan (2004) model describes a stress–coal permeability relationship, assuming a uniaxial strain and constant vertical stress. The Shi and Durucan (2004) model assumes that horizontal stresses across cleats should control coal permeability [20]. The assumption that coal permeability is governed by the mean stress under uniaxial strain is also widely used to determine coal permeability evolution. Such models can be used to evaluate the permeability anisotropy when coal cores are drilled in different directions, particularly perpendicular to the directions of cleat systems. However, such core sampling is usually not possible due to the fragility and intense fracturing of coals.

In this paper, a prediction of the permeability of coking coals, promising for CBM production, from the Leninsky area of the Kuznetsk basin was performed. The coal samples, drilled perpendicular to the butt cleat direction (i.e., in the direction of the greatest permeability of coal), were used in laboratory studies of permeability. Gas filtration was studied under hydrostatic stress conditions of cores. Coal permeability perpendicular to the face cleat direction and permeability anisotropy along the bedding planes were estimated from the results of microstructural analysis and cleat compressibility study. The regional prediction of coal permeability was performed considering the depth and features of bedding corresponding to the uniaxial strain conditions [9,20].

2. Study Site

Kuzbass is located in Russia and is one of the largest coal and methane deposits in the world (Figure 1). The predicted CBM resources are 13 trillion m$^3$. At depths of up to 1800 m, the thickness of gas-bearing coals with gas contents of up to 25–30 cubic meters per ton of a dry ashless mass (m$^3$/t) is 90–120 m. A high concentration of gas resources (up to 3.0 billion m$^3$/km$^2$), intensive underground mining of coal seams, and the presence of industrial consumers in the region determine the prospects for CBM production. CBM extraction from coking coals with permeabilities of 30–50 mD is of greatest interest [22].
Figure 1. Locations of the Nikitinsky, Tambovsky, and Tarsinsky fields in the Leninsky area, Kuzbass: (a) Kuzbass in Russia. (b) Location of the Leninsky area. (c) Locations of the fields of the coking coals and the main thrust faults in the Leninsky area. Black rectangle—the S.D. Tihov mine. (d) Significant coal seams of the Nikitinsky (II) and Tambovsky (I) fields. Legend: 1-coal seam; 2-horizon; 3-coal vitrinite reflectance; 4-gas content of coals and rocks in the certain depth interval; 5-rock crushing zones; 6-main thrust faults in the area.

Kuzbass accounts for 80% of coking coal production in Russia. Almost half of the coking coal reserves are concentrated in the Leninsky and Erunakovsky geological areas of
Kuzbass. The most valuable coking coals, characterized by an optimal maceral composition in terms of caking ability, are common in the lower layers of the Nikitinsky deposit, Leninsky area. These coals have a maximum vitrinite reflectance (R$_{0}$, max) of 0.81–1.1%, ash content on a dry basis (Ad) of 7.4–10.9%, volatile matter yield on a dry and ash-free basis (Vdaf) of 28.4–39.5%, and inertinite content of 3–19%.

The study object is the Nikitinsky coal field, which is located in the Leninsky area, Kuzbass. The Nikitinsky coal field is developed by subsurface excavation and includes the S.D. Tihov mine. The significant coking coal reserves of the Nikitinsky field are associated with thin and moderately thick seams (Figure 1).

There are also significant opportunities to increase coking coal and CBM production in the northwestern and southwestern parts of the Tarsminsky field. The Tambovsky field is also a promising target. The average total thickness of gas-bearing strata is 4.5–45 m with a gas factor of 20–35 m$^3$/t at the “–300 m” horizon (Nikitinsky field) and 14–42 m with a gas factor of 25–27 m$^3$/t at the ”–300 m” horizon (Tambovsky field) and 8–20 m at the Tarsminsky field (Figure 1). The deposits of the Nikitinsky field, containing gas-bearing coking coals, occur at depths from 730 m to 1400 m. More specifically, the industrially significant coal seams are located at depths of 815, 850, 1050, 1175, 1245, 1315, and 1350 m. The mined coal seams and roof rocks are characterized by intense fracturing. The Tambovsky field deposits, including gas-bearing coking coals, occur at depths near 1000–1960 m. The industrially significant coal seams are at depths of 1090, 1330, 1460, 1550, 1675, 1760, and 1915 m. The predicted reserves of coal and CBM are 282 million t and 7846 million m$^3$, respectively. The Tarsminsky field deposits, containing gas-bearing coking coals, occur in the range of 640–1470 m. The industrially significant coal seams are at depths of 640–680 m, 710–750 m, 810–850 m, 875–915 m, 915–955 m, 960–1000 m, 1020–1060 m, 1150–1190 m, and 1210–1250 m [22].

3. Materials and Methods

3.1. Experiments to Determine Coal Permeability and Cleat Compressibility

To determine the coal permeability, we carried out experiments using a laboratory apparatus developed at the Chinakal Institute of Mining [23]. The apparatus is designed to measure the rock gas permeability for stationary linear flow of gas. It consists of a test cell, gas preparation unit, and air-hydraulic system for axial and lateral compression of cylindrical rock samples (Figure 2). The installation provides automated maintenance of the preset pressure gradient and measurement of the permeation time of a fixed gas volume [23].

The axial compression and lateral compression of a specimen were created, respectively, by the hydraulic press $H_3$, which adds liquid at the inlet of the fourth testing cell $CA$, and by the pressure reducing valve $K_3$, from the outlet of which nitrogen from the cylinder $H_2$ flows to inlet 3 of cell $CA$ (Figure 2). The outlet pressures of press and valve were adjusted manually on the basis of the manometer readings.

The gas preparation unit $G$ (nitrogen, carbon dioxide, or methane) was composed of a filter with a water separator $B$ and the two-step reducing valve $K_1$, with $K_2$ setting the pressure $P_g$ at inlet 1 of the testing cell. The gas entered the cell, permeated through a specimen, and was fed from outlet 2 to pressure valve $K_4$, which maintained the required pressure difference $\Delta P$ between inlet 1 and outlet 2 of cell CA. For the automated adjustment and stabilization of the value $\Delta P$, an electromechanical drive was used with a step motor $M$ controlled via the computer $CO$ and the electronic module $DO1$. The back coupling was carried out by the readings of the pressure difference indicator $PP$, the output of which, via the converter $DI$ and bus $CS$, was fed to the computer.
Figure 2. Function chart of the laboratory apparatus for measuring the gas permeability of rocks: $H_1$ and $H_2$ indicate the gas cylinders; $H_3$ indicates the hydraulic press; $K_1$–$K_3$ indicate the pressure-reducing valves; $K_4$ indicates the pressure valve; $P_1$ indicates the electrovalve; $M$ indicates the electric drive of the pressure valve control; $PP$ indicates the pressure difference indicator; $DO_1$ and $DO_2$ indicate the electronic control modules; $DI_1$ and $DI_2$ indicate the bridge strain gage attachment modules; $Z_0$–$Z_3$ indicate the photo sensors of liquid level gage; $TI$ indicates the temperature sensor; $PI$ indicates the pressure sensor; $DD$ indicates the electronic module of the level gage; $C_1$ indicates the gasometer; $C_2$ indicates the liquid discharge vessel; $CO$ indicates the computer; $CS$ indicates the bus controller; $CA$ indicates the testing cell [23].

From the outlet of valve $K_4$, gas flowed to the upper inlet of gasometer $C_1$ and displaced liquid from it through the lower outlet to vessel $C_2$. The gas volume permeated through the specimen was measured by the difference in time of the liquid meniscus pass-by of certain levels in gasometer $C_1$. The level gauge consisted of LED (radiating) and photodiode (receiving) plates (Figure 2) arranged on opposite sides of the gasometer tube covered by a light-tight shield.

The receiving plate had four photosensors $Z_0$–$Z_3$ (Figure 2), a DS18B20 temperature 247 sensor ($TI$), and a NanoCH340/ATmega328P electronic module ($DD$). The liquid level gauging accuracy was 0.5 mm, the time was 1 ms, and the temperature was 0.01 °C. The spacing of the diodes of the radiating and receiving plates was 100–200 mm.

The data recording and accumulation were controlled by a program in LabVIEW. The program interrogated the sensors $Z_0$–$Z_3$, $TI$ and $PP$, $PI$ in the assigned time intervals, and controls the valves $K_4$ and $P_1$. The measurement data were given in the format [date] [time] [states of sensors $Z_0$–$Z_3$ (1 indicates that light falls at the sensor; 0 indicates that no light falls at the sensor)] [temperature] [pressure difference] [gasometer pressure].

The testing cell was designed for the uniform lateral compression of cylindrical specimens of rocks and hard construction material with a diameter $D = 30$ or 36 mm and a length $L = 30$ or 60 mm, covered with an insulating polymeric shell, and for permeation of gas through the specimen under in situ conditions. The axial load was created using the hydraulic press. The experimental procedure to determine gas permeability is described in the paper [23]. The main characteristics of the laboratory installation are given in Table 1.
Table 1. The main parameters of the laboratory apparatus used to study the gas permeability of rocks [23].

| Parameter                                | Range       | Interval of Measurements |
|-------------------------------------------|-------------|--------------------------|
| Flow time, s                              | 0.001–432,000 | 0.001                    |
| Inlet gas pressure, MPa                   | 0–5         | 0.02                     |
| Pressure difference $\Delta P$, MPa       | 0–0.3       | 0.001                    |
| Gas                                       | N2, CH4, CO2 | —                        |
| Temperature, °C                           | From −10 to +150 | 0.01                   |
| Lateral compression, MPa                  | 0–50        | 0.05                     |
| Axial compression, MPa                    | 0–50        | 0.05                     |
| Permeation volume per measurement, $cm^3$ | 0.02–0.05   | —                        |
| Weight of the cell, kg                    | 0.7         | —                        |

The coal permeability experiments were carried out using cylindrical specimens with a diameter and length of 3 cm. The specimens were drilled perpendicular to the butt cleat direction. In other directions, specimen drilling failed due to the intense fracturing and fragility of the coal.

The coal permeability experiments were carried out using nitrogen, filtered along the axial direction, with a constant pressure difference $\Delta P$ and hydrostatic pressure $P$ in the specimen. The value $P$ was varied from 1 to 8 MPa with a step of 1–2 MPa. For each value $P$, a series of laboratory tests was carried out with $\Delta P$ values from 0.01 to 0.1 MPa, varied with a step of 0.01–0.02 MPa. The experimental conditions are given in Table 2.

Table 2. Experimental conditions to determine coal permeability.

| Experimental Conditions | Coking Coals (S.D. Tihov Mine) |
|-------------------------|--------------------------------|
| Axial compression, $P$, MPa | 1, 3, 5, 7, 8 |
| Confining lateral compression, $P$, MPa | 1, 3, 5, 7, 8 |
| Pressure at inlet 1 of the test cell, $P_1$, MPa | 0.11, 0.12, 0.14, 0.16, 0.18, 0.2 |
| Pressure at outlet 3 of the test cell, $P_3$, MPa | 0.1 |
| Pressure difference, $\Delta P$, MPa | 0.01, 0.02, 0.04, 0.06, 0.08, 0.1 |
| Temperature, T, °C | 26–27 °C |

The coal gas permeability factor was calculated for stationary linear flow (Equation (1)) [24]:

$$k_g = 2 \cdot 10^4 V \mu a P_3 L \frac{1}{p_1^2 - p_3^2}$$

(1)

where $k_g$ is the gas permeability factor, mD; $P_1 = P_3 + \Delta P$ is the pressure at inlet 1 of the test cell (Figure 2), $10^{-1}$ MPa; $P_3$ is the pressure at outlet 3 of the test cell (atmospheric), $10^{-1}$ MPa; $\Delta P$ is the pressure difference, MPa; $V$ is the volume of gas flow through the sample, $cm^3$; $\mu a$ is nitrogen viscosity, mPa·s (sP); $S$ is the cross-sectional area of samples, $cm^2$; $L$ is the sample length, cm; and $t$ is the time of gas flow through sample, s. For each test series at a certain $\Delta P$, we calculated the average gas permeability factor.

The experimental research included a determination of cleat compressibility. Pore compressibility describes the relative variation in pore volume per pressure unit. Considering that the effective porosity of coal is determined by its fractures, the compressibility term is usually applied to coal cleats [25]. The cleat compressibility ratio ($C_f$) is used in many theoretical models to describe the dependence of the coal permeability on the stress conditions. Typically, coal cleat compressibility is assumed to be constant in known permeability models. The $C_f$ ratio was estimated by a method described in [26]. However, there are permeability models in which the cleat compressibility is not assumed to be a constant and is assumed to depend on the stress conditions [27]. In such cases, an initial compressibility ratio $C_0$ and a rate of compressibility ratio variation $\alpha$ are determined. The
ratio $C_0$ was determined by a method described in [26], and the ratio $\alpha$ was numerically evaluated by the method from the paper [27].

3.2. Microstructural Analysis of Coal Cleats

The properties of coal cleats were determined by the results of coal microstructural analysis, which included the determination of the cleat width, coal matrix block sizes, and angle between fracture systems. X-ray microcomputed tomography (micro-CT) is a common method to analyze rock fractures [13,28,29]. It is a nondestructive technique that produces rock three-dimensional images on the basis of the variation of X-ray attenuation in an object. This technique provides a high-resolution study of the coal microstructure, which is important to model filtration processes and numerical estimates of permeability [29]. In Zhang et al. (2016), a structural model was made on the basis of micro-CT in situ imaging, and the expected effect of coal compression on its porosity and permeability was estimated [13]. It was found that with an increase in the effective stress from 0 to 10 MPa, the width of the cleats decreased from 0.52% to 0.22%. The established morphological features of fractures were consistent with the results of filtration tests [13].

The averaged features of the coal microstructure were of interest in regional studies. Primarily, the fracture parameters (length, width, interval between cleats, etc.), characteristic of the region as a whole, can be studied using less detailed and expensive methods of optical and electron microscopy. The standard method was to measure the required parameters along 1D scanlines or line profiles. This method has several excellences: (1) it is a relatively easy and quick method; (2) several related characteristics are measured together, such as fracture width and fracture spacing; and (3) the application of the technique does not depend on the lithological composition of the rock samples and the scale of observations [30].

To perform the experiments, we used cylindrical samples drilled perpendicular to the butt cleat direction, i.e., in the direction of the maximum coal permeability. The analysis of the coal microstructure was carried out along the core longitudinal section and perpendicular to the face and butt cleat directions (plane $\alpha$) and in the plane $\beta$ (core end surface) (Figure 3). The sample surfaces were finally treated using a thin diamond paste with abrasive granules less than 0.05 micrometers ($\mu$m). Samples were subjected to additional treatment to identify structural defects with internal volume. Before the experiments, the prepared polished sections were saturated by luminophore under a low vacuum to help identify defects with internal volume. With the luminophore, EpoDye powder dissolved in alcohol at a 1:40 volume ratio was utilized. Furthermore, we dried the samples for 24 h before starting the experimental studies. A detailed description of the sample preparation is given in an earlier paper [31].

The polished rock sections were studied by reflected light using a Mineral C7 analyzer designed to measure the linear dimensions of the microstructure of solids. The analyzer included an optical microscope OLYMPUS BX51; a digital video camera SIMAGIS 2P-3C; a camera-to-PC interface module with SIAMS Photolab software installed to control sample scanning, image treatment, and analysis; and determination of the microstructure parameters. The main technical characteristics of the analyzer are shown in Table 3 [32].

Structural analysis of the tested coal included a measurement of the linear dimensions of the coal matrix block, the cleat width, and the angle between the face and butt cleats. A treatment of images was performed in the “Measurement of angles and lengths” module of SIAMS Photolab software and included preliminary treatment with stitching of images, threshold filtering and noise removal, and measurement of the linear dimensions of structural elements (Figure 4). The cleat width is taken as the distance between its two opposite walls along the scanning line. In the samples treated by luminophore, the cleat width was determined by the characteristic glow in ultraviolet light. Since the fracture crossed several line profiles, at least three measurements of the required parameters for each fracture were made. The same profiles were used to determine the linear dimensions of the coal matrix blocks and the angle between the face and butt cleats (Figure 4).
Figure 3. A simplified scheme of the studied fractured coal samples, the direction of gas filtration in laboratory tests, and the location of surfaces along which the coal microstructural analysis was performed. $\alpha$—plane perpendicular to the face and butt cleat direction, $\beta$—plane of the core end surface.

Table 3. The main characteristics of the Mineral C7 analyzer [32].

| Range of Measurement of Linear Dimensions, $\mu$m | From 0.5 to 2000 |
|-------------------------------------------------|------------------|
| The relative value of the standard deviation of the random component of the error (considering the contribution of the analyzer software), %: |                |
| - with an increase up to $\times 500$ inclusive | 0.2              |
| - with an increase over $\times 500$            | 0.4              |
| Relative error of measurement (considering the contribution of the analyzer software), %: |                |
| - with an increase up to $\times 500$ inclusive | $+/−0.25$       |
| - with an increase over $\times 500$            | $+/−0.65$       |

3.3. Data Analysis

Coal permeability was estimated utilizing known models that describe the stress-permeability relationship. The Seidle et al. (1992) model was designed to analyze laboratory coal permeability, measured under constant confining pressure conditions [33]. The absolute coal permeability under constant confining pressure conditions is determined from the following expression (Equation (2)):

$$k = k_0 \cdot e^{-3C_f (P_c - P_{c0})}$$  \hspace{1cm} (2)

where $k$ is the coal permeability, mD; $k_0$ is the permeability at the reference confining pressure $P_{c0}$, mD; $P_c$ is the confining pressure, MPa; and $P_{c0}$ is the reference confining pressure, MPa.

Robertson and Christiansen (2006) developed a model that described the dependence of coal permeability on stress conditions. The model was designed to analyze the laboratory coal permeability obtained under biaxial or hydrostatic confining pressures [34]. Coal compressibility is not constant [27]. For the conditions of a variable compression pressure and constant pore pressure, the coal permeability is defined as (Equation (3))

$$k = k_0 \cdot e^{-3C_0 \frac{1 - e^{P_c - P_{c0}}}{n}}$$  \hspace{1cm} (3)

A coal seam is typically described by a matchstick geometry model in order to develop theoretical models that address stress—permeability and porosity—permeability relationships. For the isotropic case, the fracture width and coal matrix block size are the same
for any coal cleat system. For the anisotropic case, these properties are not the same for all coal cleat systems. In the anisotropic case, a coal seam is described by an impermeable high (coal matrix) with two regular vertical fracture sets (face and butt cleats). Within a single set, every fracture has the same orientation and width, and there is a constant spacing between fractures. Simultaneously, the fracture width \( (a_f, a_b) \) and spacing between fractures \( (A_f, A_b) \) are not consistent among the various cleat systems.

![Image of coal cleats](image.png)

**Figure 4.** Coal sampling to perform microstructural analysis on planes perpendicular to the face and butt cleat direction: (a) site for manufacturing of the polished sections; (b) linear profile to measure the required parameters; (c) photo of the polished section under a microscope, which was converted into a binary form of images. 1—face cleats, 2—butt cleats.

The coal permeability was estimated for two sections perpendicular to the face and butt cleat direction: perpendicular to the butt cleat direction \( (k_b) \) and perpendicular to the face cleat direction \( (k_f) \). Coal cleats are much more permeable than the coal matrix, so the coal matrix permeability is neglected in the calculations [9]. According to earlier works [18,35], the permeability of a parallel regular fracture system is determined as (Equation (4))

\[
k_{fr} = \frac{a_{fr}^3}{12A_{fr}}
\]

where \( k_{fr} \) is the permeability of the fracture set, \( D \); \( a_{fr} \) is the fracture width, \( \mu m \); and \( A_{fr} \) is the spacing between adjacent fractures, \( \mu m \).

Considering the accepted coal seam model, the permeabilities perpendicular to the butt and face cleat directions are calculated as (Equation (5)) [35]

\[
k_f = \frac{a_f^3}{12A_f}
\]

\[
k_b = \frac{a_b^3}{12A_b}
\]

(5)
where \( k_f \) is the permeability of the face cleats, \( D; \) \( a_f \) is the face cleat width, \( \mu m; \) \( A_f \) is the spacing between adjacent face cleats, \( \mu m; \) \( k_b \) is the permeability of the butt cleats, \( D; \) \( a_b \) is the butt cleat width, \( \mu m; \) and \( A_b \) is the spacing between adjacent butt cleats, \( \mu m. \)

The effect of stresses on the coal permeability perpendicular to the face and butt cleat directions was estimated under constant confining pressure conditions utilizing known models [33,34]. The initial permeabilities of the unloaded coal perpendicular to the face and butt cleat directions were determined from the coal cleat geometric properties.

Theoretical models, considering the uniaxial strain of coal seams, were used to describe the coal permeability dependence on depth. The first model assumes that permeability is controlled by uniaxial strain and mean stress [9]. The second model describes coal permeability, controlled by the horizontal stresses across the cleats [20]. We assumed that the studied coal seams were not mined, and thus the coal matrix swelling/shrinkage effect, which arises during CBM extraction, was not considered.

For the model that describes the stress regime, defined by uniaxial strain and mean stress, the permeability is determined from Equation (6) [9]:

\[
\frac{k}{k_0} = \exp\left[-C_f \cdot 0.0131 \cdot (d - d_0) \cdot \frac{1 + \mu}{1 - \mu}\right] 
\]  

where \( k \) is the coal permeability at depth \( d, \) mD, and \( k_0 \) is the initial permeability at reference depth \( d_0, \) mD.

Assuming the Shi and Durucan (2004) model [20], in which the permeability is controlled by the horizontal stresses, the coal permeability depth dependence is described by (Equation (7))

\[
\frac{k}{k_0} = \exp\left[-3C_f \cdot 0.0131 \cdot (d - d_0) \cdot \frac{\mu}{1 - \mu}\right] 
\]

where \( k \) is the coal permeability at depth \( d, \) mD; \( k_0 \) is the initial permeability at reference depth \( d_0, \) mD; \( C_f \) is cleat compressibility, MPa\(^{-1}\); and \( \mu \) is the Poisson’s ratio of the tested coal.

4. Results
4.1. Coal Permeability and Cleat Compressibility

The experimental resulting permeability values for a different test series (\( \Delta P \) varies from 0.01 to 0.1 MPa for each \( p \)-value) are shown in Figure 3. Additionally, the average permeability values are considered. As the confining hydrostatic pressure increased by 8 times, the coal permeability decreased by 6.7 times (from 60 mD at \( P = 1 \) MPa to 9 mD at \( P = 8 \) MPa) (Figure 5). A literary analytical review indicated that these values are typical for intensely fractured coals [24]. The permeability measurement error varied from 4.8 to 7.9%.

The coal cleat compressibility \( C_f \), obtained by a method described in [26], was \( 0.0845+/-4 \times 10^{-3} \) MPa\(^{-1}\). When the cleat compressibility was not assumed to be a constant and was assumed to depend on the stress conditions, the obtained initial compressibility ratio \( C_0 \) and a rate of compressibility ratio variation \( \alpha \) were \( 0.0715+/-7.8 \times 10^{-3} \) MPa\(^{-1}\) and \( 1.83 \times 10^{-4} \), respectively [26,27]. The obtained cleat compressibility ratios \( C_f \) and \( C_0 \) and rate \( \alpha \) were utilized for further coal permeability estimation.

The coal permeability was determined according to theoretical models. The curves obtained by the Seidle el al. (1992) and Robertson and Christiansen (2006) models are shown in Figure 6. The standard deviations between the calculated and experimental data for both cases were calculated and compared. The standard deviation for the Seidle et al. (1992) model was lower than that of the Robertson and Christiansen (2006) model, and thus the Seidle et al. (1992) model more accurately described the coal permeability variation under constant confining pressure conditions [33,34]. Furthermore, the most suitable Seidle et al. (1992) model was utilized [33]. The unloaded coking coal calculated by the Seidle et al. (1992) model was 72.62 mD.
4.2. Coal Cleats

The microstructural analysis of the tested coals indicated that primary cleats were dominant in the studied coal, while secondary and tertiary fracture systems were weakly expressed. The obtained data were used to estimate the absolute permeability of coal. The coking coals had a typical block structure: a coal matrix was divided into blocks by two fracture systems (face and butt cleats) (Figure 7).
Figure 7. Structure of the fractured coking coals, S.D. Tihov mine, Leninsky area, Kuzbass; 1 indicates face cleats, 2 indicates butt cleats.

In total, for each fracture system, 450 measurements of cleat width and 130 measurements of coal matrix block size were performed. The data treatment and statistical analysis included the determination and presentation of the minimum, maximum, and average values of the measured parameters in the form of distribution histograms (Figure 8). According to the experimental results, the average width of the face cleats varied from 12.6 µm with a standard deviation of 4.5 µm. The mean size of a coal matrix block between face cleats was 2213.3 µm with a standard deviation of 426.6 µm. The mean size of a coal matrix block between butt cleats was 925 µm, with a standard deviation of 110.6 µm. The mean butt cleat width was 8.20 µm with a standard deviation of 2.9 µm (Figure 8). The average angle between the face and butt cleats was 102.3°, with a standard deviation of 6.96°.

Via experimental research, the main properties of coal cleats, cleat compressibility, and coal permeability were determined under different stress conditions, indicating that coking coal had a typical block structure with face and butt cleat systems. Earlier laboratory filtration tests were carried out perpendicular to the butt cleat direction due to the difficulties of coal core drilling. To solve this problem, we planned a special method for coal sampling with high-speed drilling by a thin-walled diamond crown and air cooling. The obtained permeability values were typical for intensely fractured coals. The veracity of the results was ensured by a sufficient amount of experimental data, statistical methods of data processing, and the use of modern equipment with high metrological characteristics.
4.3. Coal Permeability Anisotropy

The permeability anisotropy along the bedding planes were estimated from the results of the microstructural analysis and cleat compressibility study. In the calculations, the average values of the cleat width and coal matrix block size were utilized (Figure 8). The initial coal permeability values were calculated from Equation (5) and were $k_f = 74.6$ mD and $k_b = 50.4$ mD. The cleat compressibility ratio $C_f = 0.0845$ MPa$^{-1}$ was utilized in the calculations. The obtained curves, which describe the stress—permeability relationships perpendicular to the butt cleat direction and perpendicular to the face cleat direction, are shown in Figure 9.
Figure 9. Dependence of coking coal permeability (S. D. Tihov mine, Leninsky area, Kuzbass) (k) on the hydrostatic confining pressure (P) according to the Seidle et al. (1992) model and the microstructural analysis data: the blue solid line corresponds to the permeability perpendicular to the butt cleat direction; the red solid line corresponds to the permeability perpendicular to the face cleat direction.

The coal permeability was determined for confining hydrostatic pressures $P_c$ from 1 to 8 MPa. As the confining pressure increased by eight times, the coal permeability decreased by nearly six times. The coal permeability perpendicular to the butt cleat direction varied from 59.4 mD at $P_c = 1$ MPa to 10.05 mD at $P_c = 8$ MPa. Perpendicular to the face cleat direction, the coal permeability ranged from 40.11 mD at $P_c = 1$ MPa to 6.79 mD at $P_c = 8$ MPa. A comparison of the calculated and experimental results showed that the permeability ratios determined by the cleat geometric properties were on average 2.6% more than those determined by the Seidle et al. (1992) model [33]. We estimated the anisotropy of the horizontal permeability utilizing the considered established models and measured cleat properties. A 3:2 ratio of the face cleat permeability to butt cleat permeability was observed for the coals from the Leninsky area of the Kuznetsk Basin.

4.4. Coal Permeability Dependence on Depth

The coal permeability dependence on depth was estimated. Calculations were performed considering the experimentally determined cleat compressibility $C_f = 0.0845$ MPa$^{-1}$, the permeability of unloaded coal perpendicular to the butt cleat direction (74.6 mD), the 1.5 permeability anisotropy ratio, Poisson’s ratio of the tested coal $\mu = 0.31$, a lithostatic gradient appropriate for sedimentary basins (0.0231 MPa/m), and a hydrostatic gradient of the fluid pore pressure (0.01 MPa/m). For assumed pressure gradients, the vertical stress ($\sigma_v$) is (Equation (8))

$$\sigma_v = (0.0231 - 0.01) \cdot d = 0.0131 \cdot d \quad (8)$$

where $\sigma_v$ is vertical stress, MPa, and $d$ is the depth, m [9].

For the model that describes the stress regime, defined by uniaxial strain and mean stress, the permeability was determined from Equation (6) [9]. Considering the experimental data, the tested coal permeability depth dependencies perpendicular to the butt and face cleat directions were (Equations (9) and (10))

$$k_f = 74.6 / \exp[0.00206 \cdot d] \quad (9)$$

$$k_b = 50.4 / \exp[0.00206 \cdot d] \quad (10)$$
where \( k_f \) is the permeability of the face cleats, mD; \( k_b \) is the permeability of the butt cleats, mD; and \( d \) is depth, m.

Assuming the Shi and Durucan (2004) model [20], in which the permeability is controlled by the horizontal stresses, the coal permeability depth dependence can be described by Equation (7).

The corresponding coal permeability depth dependencies perpendicular to the butt and face cleat directions (Equations (11) and (12)) are, respectively,

\[
k_f = \frac{74.6}{\exp[0.00142 \cdot d]} \tag{11}
\]

\[
k_b = \frac{50.4}{\exp[0.00142 \cdot d]} \tag{12}
\]

where \( k_f \) is the permeability of the face cleats, mD; \( k_b \) is the permeability of the butt cleats, mD; and \( d \) is depth, m.

5. Discussion

For a stress regime described by uniaxial strain and mean stress, the predicted coal permeability ratios were determined from Equations (9) and (10). Assuming uniaxial strain with horizontal stress across the cleats, we determined the predicted coal permeability ratios from Equations (11) and (12). The obtained permeability depth dependencies are shown in Figures 10 and 11. Additionally, the permeability of the industrially significant coal seams of the Nikitinsky and Tambovsky fields were predicted (Tables 4 and 5). The coking coal seam name and depth data were taken from Avdeev et al. 2003 [22].

Figure 10. Permeability of the coking coals perpendicular to the butt cleat direction: permeability-depth dependence for stress regimes, described by uniaxial strain and mean stress (gray line) and horizontal stress across cleats (black line).
Figure 11. Permeability of the coking coals perpendicular to the face cleat direction: permeability depth dependence for stress regimes, described by uniaxial strain and mean stress (gray line) and horizontal stress across cleats (black line).

Table 4. The predicted coking coal permeabilities for stress regime, described by uniaxial strain and mean stress.

| Coal Seam Name | Depth, m | The Predicted Permeability of the Coking Coals Perpendicular to the Butt Cleat Direction, mD | The Predicted Permeability of the Coking Coals Perpendicular to the Face Cleat Direction, mD |
|----------------|---------|-----------------------------------------------|-----------------------------------------------|
| Nikitinsky field |         |                                               |                                               |
| 18             | 815     | 13.9                                          | 9.4                                           |
| 19             | 850     | 12.9                                          | 8.7                                           |
| 22             | 1050    | 8.6                                           | 5.8                                           |
| 26             | 1175    | 6.6                                           | 4.5                                           |
| 30             | 1245    | 5.7                                           | 3.9                                           |
| 32             | 1315    | 5                                              | 3.4                                           |
| 33             | 1350    | 4.6                                           | 3.1                                           |
| Tambovsky field |         |                                               |                                               |
| 18             | 1090    | 7.9                                           | 5.3                                           |
| 22             | 1330    | 4.8                                           | 3.2                                           |
| n/a            | 1460    | 3.7                                           | 2.5                                           |
| 30             | 1550    | 3.1                                           | 2.1                                           |
| 32             | 1675    | 2.4                                           | 1.6                                           |
| 33             | 1760    | 2                                              | 1.3                                           |
| 45             | 1915    | 1.4                                           | 1                                              |

For the Nikitinsky field, we determined that as the depth increased from 730 to 1400 m, the coal permeability decreased by 4 times (from 16.9 to 4.2 mD perpendicular to the butt cleat direction; from 11.2 to 2.8 mD perpendicular to the face cleat direction) for the case considering the uniaxial strain and mean stress and by 2.6 times (from 26.5 to 10.2 mD perpendicular to the butt cleat direction; from 17.9 to 6.9 mD perpendicular to the face cleat direction) for the case considering the uniaxial strain with horizontal stress across the cleats.
Table 5. The predicted coking coal permeabilities for stress regime, described by uniaxial strain and horizontal stress across cleats.

| Coal Seam Name       | Depth, m | The Predicted Permeability of the Coking Coals Perpendicular to the Butt Cleat Direction, mD | The Predicted Permeability of the Coking Coals Perpendicular to the Face Cleat Direction, mD |
|----------------------|----------|---------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| Nikitinsky field     |          |                                                                                             |                                                                                                |
| 18                   | 815      | 23.4                                                                                        | 15.8                                                                                            |
| 19                   | 850      | 22.3                                                                                        | 15.1                                                                                            |
| 22                   | 1050     | 16.8                                                                                        | 11.3                                                                                            |
| 26                   | 1175     | 14.1                                                                                        | 9.5                                                                                            |
| 30                   | 1245     | 12.7                                                                                        | 8.6                                                                                            |
| 32                   | 1315     | 11.5                                                                                        | 7.8                                                                                            |
| 33                   | 1350     | 11.0                                                                                        | 7.4                                                                                            |
| Tambovsky field      |          |                                                                                             |                                                                                                |
| 18                   | 1090     | 15.9                                                                                        | 10.7                                                                                            |
| 22                   | 1330     | 11.3                                                                                        | 7.6                                                                                            |
| n/a                  | 1460     | 9.4                                                                                         | 6.3                                                                                            |
| 30                   | 1550     | 8.3                                                                                         | 5.6                                                                                            |
| 32                   | 1675     | 6.9                                                                                         | 4.7                                                                                            |
| 33                   | 1760     | 6.1                                                                                         | 4.1                                                                                            |
| 45                   | 1915     | 4.9                                                                                         | 3.3                                                                                            |

Similarly, for the Tambovsky field, as the depth increased from 1000 to 1960 m, the coal permeability decreased by 7.3 times (from 9.5 to 1.3 mD perpendicular to the butt cleat direction; from 6.4 to 0.9 mD perpendicular to the face cleat direction) for the case of the uniaxial strain and mean stress and by 3.9 times (from 18.0 to 4.6 mD perpendicular to the butt cleat direction; from 12.2 to 3.1 mD perpendicular to the face cleat direction) for the case considering the uniaxial strain with horizontal stress across the cleats.

For the Tarsmsinsky field, as the depth increased from 640 to 1470 m, the coal permeability decreased by 5.5 times (from 20 to 3.6 mD perpendicular to the butt cleat direction; from 13.5 to 2.4 mD perpendicular to the face cleat direction) for the case considering the uniaxial strain and mean stress and by 3.2 times (from 30.1 to 9.3 mD perpendicular to the butt cleat direction; from 20.3 to 6.3 mD perpendicular to the face cleat direction) for the case considering the uniaxial strain with horizontal stress across the cleats.

The coal permeability obtained under the assumption of uniaxial strain and horizontal stress across the cleats was larger than the permeability obtained under the assumption of uniaxial strain with the mean stress model. In particular, the coal permeabilities obtained under the assumption of uniaxial strain and horizontal stress across the cleats were 2 times, 2.7 times, and 1.8 times larger for the coal depth range of the Nikitinsky, Tambovsky, and Tarsmsinsky fields, respectively. The predicted permeability ratios of the industrially significant coal seams are shown in Tables 4 and 5.

6. Conclusions

The high gas content of valuable coking coals in the Kuzbass predetermines the need for gas pre-drainage during field development. This creates preconditions for CBM industrial production, which is still insignificant in Russia.

As the confining pressure increased by 8 times (from 1 MPa to 8 MPa), the coal permeability perpendicular to the butt cleat direction decreased by 6.7 times (from 60 mD to 9 mD). The average coal cleat compressibility was 0.085 MPa$^{-1}$.

The tested coking coal had a pronounced microblock structure with two developed fracture systems: dominant face cleats and secondary butt cleats. In the unloaded state, the width of the face cleats was 12–13 µm, the width of the butt cleats was 8–9 µm, and the angle between them was 102.3°. The average sizes of the coal matrix microblocks between the face cleats and between the butt cleats were 2213 and 925 µm, respectively. The coal permeability anisotropy was determined by the results of filtration tests, microstructural analysis data, and the standard matchstick geometry model of coal. It was found that a
3:2 ratio of face cleat permeability to butt cleat permeability was observed for coals from the Leninsky area, Kuzbass.

On the basis of the obtained experimental and analytical data, we predicted the permeability for gas-bearing coking coals of the Nikitinsky, Tarsminsky and Tambovsky deposits of the Leninsky district, Kuzbass. The dependences of coal permeability change on depth were obtained. The prediction was performed assuming conditions of uniaxial strain of rocks, which made it possible to model the stress–strain state of horizontal layers on a regional scale. It was found that in the depth intervals of the coking coals, as the depth increased, their permeability decreased by 61–75% in the Nikitinsky field and by 74–87% and 69–82% in the Tambovsky and Tarsminsky fields, respectively. The permeability anisotropy coefficient along the bedding plane was 1.5, which can be used to design gas drainage schemes for the considered coals.

The obtained results showed the perspective of industrial CBM production from gas-bearing coking coal seams in the Leninsky area, Kuzbass. Taking into account the poor knowledge of the regularities of coal permeability changes in the region, we can say that the obtained results are of practical interest and can be used to select promising objects and to design industrial operations for CBM extraction in Kuzbass.

**Author Contributions:** Conceptualization, T.S. and S.S.; methodology, T.S.; validation, T.S. and S.S.; formal analysis, S.S.; investigation, T.S.; writing—original draft preparation, T.S.; writing—review and editing, S.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Russian Science Foundation, grant number 19-77-00069.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Lin, B.; Song, H.; Zhao, Y.; Liu, T.; Kong, J.; Huang, Z. Significance of gas flow in anisotropic coal seams to underground gas drainage. *J. Pet. Sci. Eng.* 2019, 180, 808–819. [CrossRef]
2. Guo, P.; Cheng, Y.; Jin, K.; Li, W.; Tu, Q.; Liu, H. Impact of Effective Stress and Matrix Deformation on the Coal Fracture Permeability. *Transp. Porous Media* 2014, 103, 99–115. [CrossRef]
3. Karacan, C.O.; Ruiz, F.A.; Cotè, M.; Phipps, S. Coal mine methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction. *Int. J. Coal Geol.* 2011, 86, 121–156. [CrossRef]
4. Guo, X.; Yan, Q.; Wang, A. Evaluation of Relative Permeability in Coalbed Methane Reservoirs Based on Production Data: A Case Study in Qinshui Basin, China. *Nat. Resour. Res.* 2018, 28, 187–198. [CrossRef]
5. Liu, Q.; Chu, P.; Hao, C.; Cheng, Y.; Wang, H.; Wang, L. Non-uniform Distributions of Gas Pressure and Coal Permeability in Coalbed Methane Reservoirs Induced by the Loess Plateau Geomorphology: A Case Study in Ordos Basin, China. *Nat. Resour. Res.* 2019, 29, 1639–1655. [CrossRef]
6. Pan, Z.; Connell, L.D. Modelling permeability for coal reservoirs: A review of analytical models and testing data. *Int. J. Coal Geol.* 2012, 92, 1–44. [CrossRef]
7. Cui, X.; Bustin, R.M. Volumetric strain associated with methane desorption and its impact on coalbed gas production from deep coal seams. *AAPG Bull.* 2005, 89, 1181–1202. [CrossRef]
8. Thakur, P. *Advanced Reservoir and Production Engineering for Coal Bed Methane*; Elsevier BV: Amsterdam, The Netherlands, 2017.
9. Seidle, J. *Fundamentals of Coalbed Methane Reservoir Engineering*; PennWell Books: Tulsa, OK, USA, 2011.
10. Serdyukov, S.V.; Kurlenya, M.V.; Rybalkin, L.A.; Shilova, T.V. Hydraulic Fracturing Effect on Filtration Resistance in Gas Drainage Hole Area in Coal. *J. Min. Sci.* 2019, 55, 175–184. [CrossRef]
11. Tan, Y.; Pan, Z.; Liu, J.; Zhou, F.; Connell, L.D.; Sun, W.; Haque, A. Experimental study of impact of anisotropy and heterogeneity on gas flow in coal. Part II: Permeability. *Fuel* 2018, 230, 397–409. [CrossRef]
12. Gash, B.W.; Volz, R.F.; Potter, G.; Corgan, J.M. The effect of cleat orientation and confining pressure on cleat porosity, permeability and relative permeability in coal. In Proceedings of the International Coalbed Methane Conference, SPWLA/SCA Symposium, Oklahoma City, OK, USA, 14–17 June 1992; pp. 15–16.
13. Zhang, Y.; Xu, X.; Lebedev, M.; Sarmadivaleh, M.; Barifcani, A.; Iglauer, S. Multi-scale x-ray computed tomography analysis of coal microstructure and permeability changes as a function of effective stress. *Int. J. Coal Geol.* 2016, 165, 149–156. [CrossRef]
14. Kurlenya, M.V.; Serdyukov, S.V.; Patutin, A.V.; Shilova, T.V. Stimulation of Underground Degassing in Coal Seams by Hydraulic Fracturing Method. *J. Min. Sci.* 2017, 53, 975–980. [CrossRef]
15. Pan, Z.; Connell, L.D. Modelling of anisotropic coal swelling and its impact on permeability behaviour for primary and enhanced coalbed methane recovery. *Int. J. Coal Geol.* **2011**, *85*, 257–267. [CrossRef]
16. Wang, D.; Lv, R.; Wei, J.; Zhang, P.; Yu, C.; Yao, B. An experimental study of the anisotropic permeability rule of coal containing gas. *J. Nat. Gas. Sci. Eng.* **2018**, *53*, 67–73. [CrossRef]
17. Wang, J.; Liu, J.; Kabir, A. Combined effects of directional compaction, non-Darcy flow and anisotropic swelling on coal seam gas extraction. *Int. J. Coal Geol.* **2013**, *109–110*, 1–14. [CrossRef]
18. Somerton, W.; Söylemezoğlu, İ.; Dudley, R. Effect of stress on permeability of coal. *Int. J. Rock Mech. Min. Sci. Géomeéch. Abstr.* **1975**, 12, 129–145. [CrossRef]
19. Palmer, I. Permeability changes in coal: Analytical modeling. *Int. J. Coal Geol.* **2009**, *77*, 119–126. [CrossRef]
20. Shi, J.-Q.; Durucan, S. A Model for Changes in Coalbed Permeability during Primary and Enhanced Methane Recovery. *SPE Reserv. Eval. Eng.* **2005**, *8*, 291–299. [CrossRef]
21. Palmer, I.; Mansoori, J. How Permeability Depends on Stress and Pore Pressure in Coalbeds: A New Model. *SPE Reserv. Eval. Eng.* **1998**, *1*, 539–544. [CrossRef]
22. Avdeev, A.P.; Cherepovskiy, V.F.; Sharov, G.N.; Uzvickiy, A.Z. Coal Base of Russia. Volume II. Coal Basins and Deposits of Western Siberia (Kuznetsk, Gorlovsky, West.-Siberian Basins; Deposits of Altai Region. and Altai Republic); Geoinform Center: Moscow, Russia, 2003. (In Russian)
23. Serdyukov, S.V.; Shilova, T.V.; Droghich, A.N. Laboratory Installation and Procedure to Determine Gas Permeability of Rocks. *J. Min. Sci.* **2017**, *53*, 954–961. [CrossRef]
24. Sander, R.; Pan, Z.; Connell, L.D.; Camilleri, M.; Heryanto, D. Experimental Investigation of Gas Diffusion in Coal—Comparison Between Crushed and Intact Core Samples. In Proceedings of the SPE Asia Pacific Oil & Gas Conference and Exhibition, Society of Petroleum Engineers, Perth, Australia, 25–27 October 2016. [CrossRef]
25. Laubach, S.E.; Marrett, R.A.; Olson, J.E.; Scott, A.R. Characteristics and origins of coal cleat: A review. *Int. J. Coal Geol.* **1998**, *35*, 175–207. [CrossRef]
26. Pan, Z.; Connell, L.D.; Camilleri, M. Laboratory characterisation of coal reservoir permeability for primary and enhanced coalbed methane recovery. *Int. J. Coal Geol.* **2010**, *82*, 252–261. [CrossRef]
27. McKee, C.R.; Bumb, A.C.; Koenig, R.A. Stress-Dependent Permeability and Porosity of Coal and Other Geologic Formations. *SPE Form. Eval. 1988*, 3, 81–91. [CrossRef]
28. Karimpouli, S.; Tahmasebi, P.; Ramandi, H.L. A review of experimental and numerical modeling of digital coalbed methane: Imaging, segmentation, fracture modeling and permeability prediction. *Int. J. Coal Geol.* **2020**, *228*, 103552. [CrossRef]
29. Ramandi, H.L.; Mostaghim, P.; Armstrong, R.T.; Saadatfar, M.; Pinczewski, W.V. Porosity and permeability characterization of coal: A micro-computed tomography study. *Int. J. Coal Geol.* **2016**, *154–155*, 57–68. [CrossRef]
30. Bandyopadhyay, K.; Mallik, J.; Ghosh, T. Dependence of fluid flow on cleat aperture distribution and aperture–length scaling: A case study from Gondwana coal seams of Raniganj Formation, Eastern India. *Int. J. Coal Sci. Technol.* **2019**, *7*, 133–146. [CrossRef]
31. Tanaino, A.S.; Sivolap, B.B.; Maksimovsky, E.A.; Persidskaya, O.A. Method and means to estimate porosity distribution on the surface of polished section of coal. *J. Min. Sci.* **2016**, *52*, 1216–1223. [CrossRef]
32. Analyzers of Fragments of the Microstructure of Solids. Available online: https://all-pribors.ru/opisanie/27438-10-26089 (accessed on 30 April 2020). In Russian.
33. Seidle, J.P.; Jeansonne, M.W.; Erickson, D.J. Application of Matchstick Geometry to Stress Dependent Permeability in Coals. In Proceedings of the SPE Rocky Mountain Regional Meeting, Casper, WY, USA, 18–21 May 1992; pp. 433–444. [CrossRef]
34. Robertson, E.P.; Christiansen, R.L. A Permeability Model for Coal and Other Fractured, Sorptive-Elastic Media. In Proceedings of the SPE Eastern Regional Meeting, Canton, OH, USA, 11–13 October 2006; pp. 1–12. [CrossRef]
35. Parsons, R. Permeability of Idealized Fractured Rock. *Soc. Pet. Eng. J.* **1966**, *6*, 126–136. [CrossRef]