Assessment of properties of coal seams as destructible environments

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Abstract. The article analyzes indexes that characterize properties of coal seams and are used in calculation of loads on cutting tools of mining machines, or in selection of drives. Determination of geological structure complexity of coal seams takes into account hard inclusions and dirt bands in coal, as well as their size and lithology type. The notion of coal cuttability in spalled and unspalled face zones is explained using the coefficient of coal spalling. For strength estimation of complex structure coal seams with dirt bands and hard inclusions, it is proposed to use the index of integral cuttability which is the sum of coal cuttability and generalized index of densities and properties of inhomogeneities in the seam. In geological documentation, strength characteristics of inhomogeneities are described using the ultimate compression strength or Protodyakonov factor of hardness (in Russia). For this reason, the authors propose an empirical expression to recalculate cuttability of inhomogeneities in terms of uniaxial compression strength or hardness factor. The estimation algorithms of brittleness, grindability and breakability of coal seams are presented. The formula of coal abrasiveness is given. Systematization of data on breakability of coal seams has made a framework for classification of coal seams as media disintegrated by cutting tools of mining machines.

1. Introduction

Even though the share of coal generation in the modern world is gradually decreasing, its share is still quite large and is about 40%. In this regard, issues related to sustainable and uninterrupted coal production are relevant [1-4].

Modern ideas about the properties of coal seams as objects of destruction by cutters of coal-mining machines are based mainly on the following works of Russian scientists [6; 9] and foreign scientists [7; 8; 10-20] considering joint study of coal seams and fracture processes. The obtained parameters of the strength properties of the layers serve as the basis for the calculations of the power requirements of coal mining machines.

Russian researchers use mainly experimental and statistical methods, which distinguish them from the studies of foreign authors that are based on physical representations of the laws of the processes of
cutting coal and rocks. As the main indicator that determines the properties of coal seams Russian scientists recommended [5-6; 9; 21; 22] the cuttability of coal seam. To measure this value as an integral strength property depending on the complexity of coal seams structure and geological factors [6; 21; 23] the special equipment and techniques have been created [22; 24]. The complexity of coal seams structure and geological factors includes the abrasiveness of coal seams and the content of solid inclusions in them [25], the ability of coal to grind during cutting, their destructibility and brittle-plastic properties [26; 27].

In general, the above-mentioned studies of Russian scientists allowed classifying coal seams according to their cuttability and geological structure [23].

Among foreign researchers, special attention should be paid to the studies of I. Evans and S. Pomeroy [10; 11], who were among the first to propose models and give a physical interpretation of the laws of the processes of coal destruction during cutting. The first such model [10] was proposed by Evans in relation to the determination of the cutting force. According to this model, when the cutting tool is inserted into a seam, radial compressive stresses occur in it and when they reach the tensile strength of the material, a cleavage occurs in the form of a symmetrical V-shaped fragment. This assumes that there is no friction between the tool and the rock and assumes that the normal contact pressure between the cutter and the rock mass is evenly distributed. Later, Goktan R. improved the theory of cutting Evans applied to cutting rocks cutters with a conical shape of the cutting part [12].

Along with theoretical methods, numerical methods to describe the destruction of rocks with a cutting tool have been developed. For example, in [19] the destruction of rocks by a tangential cutter was studied in two-dimensional and three-dimensional formulations, and in [20] the finite difference method was used in the three-dimensional formulation of the problem using the Particle Flow Code (PFC) algorithm. The authors explained the choice of the discrete element method tool for numerical modeling by the fact that this method allows modeling a rock mass as a collection of particles with different properties, including pores, cracks, cavities, etc. [27]. The study consisted in comparing the results of numerical modeling with laboratory test data and calculated values. It was noted that the results of numerical modeling and theoretical calculations agree well with each other, but poorly with laboratory data.

Paying tribute to the authors of the studies above, it should be noted that the theoretical models of destruction of coal and rocks by the cutters proposed by them are made with multiple assumptions and simplifications. The main of them are the followings: cutting is considered as a two-dimensional process, while it is believed that there is no interaction between adjacent cuts, ignored the presence of solid inclusions and strong rock layers in coal seams, as well as possible fractures in coal seams during their destruction [8; 10; 14; 27].

Summarizing the results of research by scientists from Russia and other countries, it should be noted that in relation to the description of the efficiency of the operation of coal mining machines, it is necessary to determine a set of characteristics that best reflect the process of destruction of the coal seam. At this, it is especially important that such characteristics should affect the failures of cutterheads. Ultimately, it is necessary to determine and justify a generalized criterion for the properties of destructible coal seams, which would comprehensively evaluate layers of complex structure as environments destroyed by cutterheads of coal mining machines.

For efficient coal mining as well as mining machinery design and operation coal seams should be assessed by taking jointly:

- Structural characteristics;
- Breakability indexes (cuttability and brittleness).

Structural heterogeneities of coal seams have influence on loading and reliability of mining machines and should primarily be considered when selecting parameters of cutting tools and transmissions.
Properties of a coal mass are variable, which is mainly caused by in homogeneities (dirt bands and hard inclusions) and by rock pressure effects. For this reason, physical magnitudes turn out to be inadequate for the description of a coal seam as a destruction object. It is advisable to use process variables of coal seam breakability as they allow integral assessment of coal seams as media destroyed by cutting tools of mining machines.

In Russia engineering designs use such characteristics as: cuttability of coal, $A_{\text{coal}}$, N/mm, and coal seam, $A_{\text{seam}}$, N/mm, hard inclusions $A_{\text{hard}}$, N/mm, and dirt bands, $A_{\text{dirt}}$, N/mm, densities of hard inclusions, $S_{\text{hard}}^*$, %, and dirt bands, $S_{\text{dirt}}^*$, %; coal seam abrasiveness $\rho$ (mg/km); coal brittleness $B$ and grindability $m$, which are dimensionless values.

2. Materials and methods
The aim of the study is to evaluate the properties of coal seams as destructive media. The following tasks are set in the work:

- Assess the complex geological structure of coal seams;
- Assess the fragility and grind ability of coal, the level of destructibility of coal beds;
- Present a classification of coal seams by fragility and geological structure.

The work uses scientific and experimental methods, which made it possible to conduct an experiment and evaluate coal seams as destructive media.

3. Results
Structural complexity of coal seams is governed by dirt bands and inclusions harder than coal. Hard inclusions commensurable in size with cutting depth essentially add to load on cutting tools (especially dynamic load) and worsen operation of mining machines.

Hard inclusions are divided into types with regard to their dimension as per data in table 1.

| Type of inclusion | Length, cm | Thickness, cm | Cross section, cm$^2$ |
|------------------|------------|---------------|-----------------------|
| Fractured        | To 0       | To 5          | To 50                 |
| Unfractured      | 10–30      | 5–10          | 50–300                |
| Consolidated     | Larger than 30 | More than 10 | Larger than 300      |

Lithology types of hard inclusions are diverse. Most often there are carbonate-bearing hard inclusions divided into 4 groups of petrography: carbonate (calcite) K1; carbonate (siderite) K2; carbonate K3; carbonate K4. In coal geology, the carbonate inclusions are mostly named as pyrites. The hard carbonate inclusions widely range in size. However, their length (from 40 to 315 cm.) generally essentially exceeds their thickness (from 15.5 to 45 cm.).

The carbonate inclusions have various strength characteristics. Their ultimate compression strength $\sigma_{\text{com}}$ ranges from 51.0 to 74.7 MPa and is on average 65.3 MPa. Pyrite inclusions show the highest strength ($\sigma_{\text{com}} = 107.4–117.6$ MPa), although their small size, according to practice, has minor influence on efficiency of coal mining machines. Conversely, large and numerous consolidated hard inclusions, if present, greatly complicate operation conditions of cutting tools, which limits capacity of the machines in the long run.

In calculations connected with determination of load on cutting tools or with choice of electric drives, hard inclusions or dirt bands are estimated by the index of their density in coal seams. The density of inclusions (dirt bands) is determined by their specific area found from the formula:
\[ S' = 100 \sum_{i} \frac{S_i}{F} \]  

where \( \sum S \) is the total cross-section area of hard inclusions or dirt bands in the measurement interval along the face, \( m^2 \); \( F \) is the exposed area of the face, \( m^2 \).

Based on the information about the number and types of hard inclusions from the mine geology documentation, their density in a coal seam may approximately be assumed as in table 2.

| Number of hard inclusions per 100 m of the face length | Fractured | Unfractured | Consolidated |
|-------------------------------------------------------|-----------|-------------|--------------|
| 10                                                    | 0.05      | 0.3         | 1.5          |
| 20                                                    | 0.1       | 0.6         | 3.0          |
| 100                                                   | 0.5       | 3.0         | 15.0         |

Density of hard inclusions in coal seams having different thickness and number of inclusions per 100 m of face length than the seams in Table 2 is determined by interpolation.

The strength characteristics of dirt bands, similarly to hard inclusions, vary in wide ranges within a single lithology type. Sand bands feature the highest strength (lithology types P4–A1 and A1–P4): their ultimate compression strength \( \sigma_{\text{com}} = 53.0–101.8 \, \text{MPa} \) and the Protodyakonov index of hardness \( f = 5.9–8.0 \).

The softest rocks are argillite (lithology types \( \text{Ar}_1, \text{Ar}_2 \)) and carbonaceous argillite (\( \text{Ar}_c \)). The ultimate compression of argillites varies from 16.6 to 34.6 MPa and \( f = 1.5–2.7 \). Siltstone takes intermediate position between sandstone and argillite although the compression strength also ranges widely: \( \sigma_{\text{com}} = 23.0–55.5 \, \text{MPa}; A_{\text{dirt}} = 208–565 \, \text{N/mm}, f = 2.8–5.0 \).

Density of dirt bands in the assessment of coal breakability is determined similarly to density of hard inclusions. Average thickness of a dirt band per face length is determined together with the number of dirt bands, their lithology types and density of each lithology type (in case there are more than one dirt bands); then, the average cuttable thickness of coal seam is found.

The cuttability is understood as the ability of coal to sustain mechanical attack of a cutter of standard geometry. The cuttability index is assumed as \( A \), which is the increment in the cutting force per 1 cm. depth of cutting by a measurement cutter with a cutting edge 2 cm. wide, equipped with a force gage, in a standardized mode.

\[ A = \frac{Z}{h} \]  

where \( A \) is the cuttability, N/mm; \( Z \) is the cutting force, N; \( h \) is the cut depth, mm.

In operating mines in Russia, cuttability of coal is determined using drilling dynamometers. The method consists in drilling-out of a pre-drilled hole with a diameter of 42 mm, at a constant drill feed, with record registration of change in the cutting resistance moment.

Depending on the problems to be solved, cuttability of coal is determined in spalled and unspalled zones.

Cuttability of coal in unspalled zone \( A_{\text{coal}} \) is determined deep in rock mass free from spalling. Owing to this, this is the most stable value and, therefore, is used as the base classification indicator of application areas for coal mining machines.

Cuttability of coal in face area \( A_{\Phi} \) is lower than in unspalled zone due to rock pressure. The zone of rock pressure manifestation is named a spalling zone (as a rule, makes 0.4–0.6 m of coal seam thickness) and a pronounced spalling zone (10–20 cm deep brim of the face). Cutters of mining
machine drum operate, partly or totally, within the spalling zone; for this reason, the cuttability of coal for mining machine with the cutting width is found from the expression:

\[ B_{\text{spall coal}} = A_k A \]  

where \( A_k \) is the spalling coefficient which is a ratio of coal cuttability in unspalled zone to average cuttability of coal in operation zone of cutting drum.

It is experimentally found that the average coefficient of spalling for a cutting drum with the cutting width \( B_{\text{cut}} \) is given by:

\[ k_{\text{spall}} = k_{\text{spall,0}} + \left( \frac{B_{\text{cut}}}{H_{\text{seam}}} \right) c + \left( \frac{B_{\text{cut}}}{H_{\text{seam}}} \right) d \]

where \( k_{\text{spall,0}} \) is the coefficient of spalling at the face edge; \( H_{\text{seam}} \) is the coal seam thickness, m; \( c \) and \( d \) are the coefficients depending on coal quality and mining conditions. The calculations usually assume: \( c = 0.1 \) for a hard coal, 0.15 – for a lignite coal, \( d = 1.0 \) for \( B_{\text{cut}} < 1.2 \text{ m} \), 1.3 for \( B_{\text{cut}} > 1.2 \text{ m} \).

Integral cuttability index of coal seam - \( A_x \), N/mm. Coal seams contain usually both dirt bands and hard inclusions. In these cases, it is proposed to assess such complex-structure seams using the integral cuttability index \( A_x \), N/mm.

\[ A_x = A_{\text{coal}} + A_{\text{inh}} \]

where \( A_{\text{inh}} \) is the generalized index of density and properties of inhomogeneities (dirt bands, cutbacks, hard inclusions) in coal seam, N/mm.

The value \( A_{\text{inh}} \) characterizes level and frequency of maximum loads arising in cutters and responsible for the cutting process dynamics and cause abrupt failures in destruction of complex-structure coal seams. This index is calculated from:

\[ A_{\text{inh}} = A_{\text{hard}} + A_{\text{dirt}} \]

where \( A_{\text{hard}} \) is the generalized index of density and properties of hard inclusions, N/mm; \( A_{\text{dirt}} \) is the generalized index of density and properties of dirt bands, N/mm:

\[ A_{\text{hard}} = 1.5A_{\text{hard}} K_{\text{hard}} S_{\text{hard}} d_{\text{hard}} \text{, N/mm} \]

\[ A_{\text{dirt}} = A_{\text{dirt}} K_{\text{dirt}} S_{\text{dirt}} \text{, N/mm} \]

where \( S_{\text{hard}} \), \( S_{\text{dirt}} \) are the densities of hard inclusions and dirt bands in coal seam, respectively, %.

The coefficient \( K_{\text{inh}}(K_{\text{hard}}, K_{\text{dirt}}) \) is given by:

\[ K_{\text{inh}} = \frac{A_{\text{inh}} - A_{\text{coal}}}{A_{\text{coal}}} \]

Ratio of cutback inclusions by cutters \( d_{\text{hard}} \) is advised to be accepted as 0.87 for fractured inclusions, 0.9 for unfractured inclusions and 0.99 for consolidated inclusions.
It is difficult to show the influence exerted by each of \( A_{\text{hard}} \) and \( A_{\text{dirt}} \) on \( A_{\text{inh}} \). This is explained by the fact that the weight of each index is comprised of a series of characteristics such as thickness of an inclusion or dirt band, cuttability, lithology type. But otherwise, hard inclusions having high cuttability but low density in a coal seam have weaker effect on \( A_{\text{inh}} \) than a thick dirt band of lower cuttability. Physically, the index \( A_{\text{inh}} \) means reduced cuttability of inhomogeneities (with regard to \( S_{\text{hard}}^* \) and \( S_{\text{dirt}}^* \)).

The analysis of the expression (5) shows that \( A_{\text{inh}} \) is either always equal to \( A_{\text{coal}} \) (in coal seams of simple structure), or higher than \( A_{\text{coal}} \); in the latter case, the difference grows with the density of inclusions in the coal seam and with the discrepancy between the cuttabilities of coal and inclusions.

One of the main factors to govern the value of \( A_{\text{coal}} \) and \( A_{\text{inh}} \), and, consequently, loads imposed on cutters is the presence and cuttability of hard inhomogeneities in coal seams (hard inclusions, dirt bands and cutback host rocks). Mine geological documents on coal seams characterize strength of inhomogeneities by the ultimate compression strength \( \sigma_{\text{com}} \) or by the Protodyakonov index of hardness \( f \) (in Russia).

The analysis of the experimental data on strength characteristics of hard inclusions and dirt bands discloses a correlation between them depicted in figure 1.

![Figure 1](image.png)

**Figure 1.** Relationship between cuttability \( A_{\text{inh}}^* \), uniaxial compression strength \( \sigma_{\text{com}} \) and Protodyakonov index of hardness \( f \) of inhomogeneities in coal seam.

The empirical expressions to describe the relationships in Figure 1 are given by:

\[
A_{\text{inh}}^* = 0.3 \sigma_{\text{com}}^{1.19} \quad (10)
\]

\[
A_{\text{inh}}^* = 56.3 f^{1.35} \quad (11)
\]

Regarding the latter expression (7) and (8), we rewrite the formulas for the generalized index of density and properties of inhomogeneities in coal seam as follows:

- By mentioned \( \sigma_{\text{com}} \):

\[
A_{\text{inh}}^* = \sigma_{\text{com}}^{1.19} (0.45 \bar{K}_{\text{hard}} S_{\text{hard}}^* d_{\text{hard}} + 0.3 \bar{K}_{\text{dirt}} S_{\text{dirt}}^*) \quad (12)
\]
By mentioned $f$:

$$A'_{\text{inh}} = f^{1.35} (84.4K_{\text{hard}}S'_{\text{hard}}d_{\text{hard}} + 56.3K_{\text{dirt}}S'_{\text{dirt}})$$

The obtained relations $A'_{\text{inh}} = f(\sigma_{\text{com}})$ and $A'_{\text{inh}} = f (f)$ enable finding $A'_{\text{inh}}$ at the known values of $\sigma_{\text{com}}$ and $f$, which makes it possible to calculate the index of equivalent cuttability $A$ of coal given there is any available geological information on strength characteristics of inhomogeneities, and this essentially simplifies computation.

It is known that for any process connected with cutting of coal and rocks, it is valued that the rate (efficiency) of the process, any other conditions being equal, is proportional to the cutting power $P$ and inversely proportional to the exposed coal area $S$ and specific energy intensity of cutting $N_w$. For instance, the feed velocity $v_{\text{feed}}$ is calculated as:

$$v_{\text{feed}} = \frac{P}{60B_{\text{cut}}H_{\text{seam}}H_w}, \text{ m/min}$$

where $P$ is the cutting power, kW; $B_{\text{cut}}$ is the cut width, m; $H_{\text{seam}}$ is the cuttable thickness of coal seam, m.

Thus, at the known values of $P$, $B_{\text{cut}}$ and $H_{\text{seam}}$ in (14), the capacity of a mining machine (feed velocity) is unambiguously determined by the inverse proportion to the energy intensity of destruction (cutting).

Since the energy of cutting is spent to deformation of rocks in the cutting zone, as well as to separation and partial grinding of chips, the total energy intensity of the process is composed of the energy intensities of each process stage, is an integral characteristic of the process and, consequently, can be used to estimate breakability of coal.

On the other hand, under reference modes, the cutting energy intensity is directly proportional to the cutting force $Z$ and inversely proportional to the cut cross-section $S$ governed by the brittle–plastic properties of coal, which are commonly assessed by the side cutting edge angle $\phi$:

$$H_w = k \frac{Z}{S} = ZL \frac{A}{S} \frac{V}{b (b + h \cdot \text{tn}(\phi))}$$

where $k$ is the constant of proportionality; $L$ is the cutting path, cm; $V$ is the volume of broken material, cm$^3$; $A$ is the cuttability, kgf/cm; $b$ is the width of the active part of cutter, cm; $h$ is the cut depth, cm.

The research into cutting of cement-and-coal blocks experimentally found the interaction:

$$\text{tn}(\phi) = Bh^{0.5}$$

Placing the latter relation in (15) yields:

$$H_w = \frac{A}{b (b + Bh^{0.5})}$$

In Russian mining practice $B$ is named as the index of brittleness and describes the influence exerted by brittle–plastic properties of coal on energy intensity of cutting. The higher $B$ means that coal is more brittle and its cutting consumes less energy, the other conditions being equal.

Thus, brittleness is understood as ability of coal to break with a certain energy at the same cuttability and constant parameters of the cutting mode. The range of brittleness is: $B = 1.3…8.0$. Qualitatively, by the index $B$, coal is split into viscous ($B<2.1$), brittle ($B>2.1…3.5$) and very brittle ($B>3.5$).

It is also found, that the value of $B$ correlates with the index $m$ denoted as the coal grindability:
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2.3

\[ B = \frac{e^{2.1m}}{m^2 - 8.4} \]  

Numerical values of \( m \) are determined from the nomograms plotted based on the data of screen analysis of coal sampled from face area. To this effect, the averaged undersize values are plotted as functions of mesh sizes on the functional network of distribution of granulometric constituents (figure 2). Then, the resultant points are used to draw a straight line, and the index \( m \) is determined as the tangent of the angle to the X-axis: \( m = b/a \).

Figure 2. Graphical method of coal grindability determination.

It is found, that the grains-size distribution of broken coal obeys the law:

\[ W = 1 - \exp(\lambda d^m) \]  

where \( W \) is the total output (fractions of sample mass) of broken coal penetrated through the sieve with the mesh size \( d \), mm; \( \lambda \) is the grindability parameter governed by the accepted methods and modes of cutting.

The index of coal grindability is taken as a basis in engineering design of coal brittleness and is used in classification of coal seams by dust-making ability (Bilgin, Copur and Balci, 2014).

Considering that cutting energy intensity is governed by the cuttability \( A \) and brittleness \( B \) in the formula (17), it is proposed to rank coal seams into seven breakability categories—from very weak to extra strong. In this case, breakability of coal and coal seams under mechanical attacks is interpreted as the ability to break at the certain energy consumption under constant operating conditions. Numerically, the breakability criterion \( R \) (kW·h·cm/m³) of coal seam is found from the expression:
where $A$ is the cuttability defined by the coal cuttability $A_{\text{coal}}$, or by the integral cuttability of coal seam $A_{e}$.

It is found that $R$ varies from 2.4 to 65 in separate coal seams, which is a wide range sufficient for solution of engineering problems. It is analytically determined that the higher influence on $R$ is exerted by the index of cuttability: as it grows from 60 to 480 N/mm at the constant $B$, the value of breakability increases 7–14 times. Oppositely, under the variation in brittleness at the constant cuttability, $R$ raises only 1.6–3.2 times.

Figure 3 shows the nomogram for determination of breakability of coal seams. Here, the boundaries of each category are the lines of equal energy consumption.

![Figure 3. Nomogram to determine values and categories of coal breakability.](image)

The points in Figure 3 stand for coal seams with different values of $A_{\text{seam}}$ and $B$. The curve depicts the probable boundary of change in the values of $B$.

Abrasiveness of coal seams is governed by dirt bands and hard inclusions present in the seam. Estimation of coal abrasiveness uses the abrasiveness index $\rho$ (mg/km) found experimentally. The procedure of coal seam abrasiveness estimation (Evans I, 1962) is based on attrition of a reference tool made of steel grade 45 having hardness HRC 24 ± 1 in reference operating conditions. The attrition test specimen is made of crushed components (coal, hard inclusions, dirt bands) taken proportionally to their content in coal seam. During the attrition tests, the pressure at the specimen–tool contact is constant.

With the known data on abrasiveness of coal seam components, the overall abrasiveness can be calculated from the formula:

$$R = 0.38 \frac{A}{B + 1} \quad (20)$$

$$\rho_{\text{seam}} = \rho_{\text{coal}} S_{\text{coal}} + \sum_{i=1}^{n} \rho_{\text{dirt}} S_{\text{dirt}_i} + \sum_{j=1}^{m} \rho_{\text{hard}} S_{\text{hard}_j} \quad (21)$$
where \( \rho_{\text{coal}}, \rho_{\text{dir}}, \rho_{\text{hard}} \) are, respectively, the average abrasiveness of coal, dirt bands and inclusions of an \( i \)-th lithology type; \( n \) and \( m \) are the numbers of lithology types of dirt bands and hard inclusions; \( S_{\text{coal}}, S_{\text{dir}}, S_{\text{hard}} \) are the densities (content) of the components in coal seam.

Systematization of data on breakability of coal seams and, owing to this, possibility to carry out an integrated assessment of strength characteristics of coal has made a framework for classification of coal seams as media destroyed by rock-breaking tools of mining machines (Dokukin A.V., Chirkov S.E and Norel B.K, 1981). On the whole, the classification is based on typification of coal seam structure with regard to different lithology types of dirt bands and various-size hard inclusions in the seams, as well as on division of coal seams into categories of breakability as function of cuttability and brittle–plastic properties of coal. Typification of coal seams by geological structure is given in table 3.

From the analysis of Table 3 data, as cuttability and density of inhomogeneities in coal seam increases, the generalized index naturally grows. For instance, in simple structure seams, or in seams containing small dirt bands and hard inclusions (typical condition group 1), the generalized index ranges between 0 and 52 N/mm, while in group 3 (high density and hardness of inhomogeneities), the index jumps to 523 N/mm and is on average 163 N/mm. Practical experience shows that such conditions limit productivity and reliability of coal mining machines.

**Table 3. Density of hard inclusions in coal seam**

| Group of structural complexity of coal seams | Description | Generalized index \( A_{\text{inh}} \) |
|--------------------------------------------|-------------|-----------------------------------|
| 1                                          | Seams of pure coal or with bands of coaly argillite and (or) argillite with cuttability \( A_{\text{dir}} < 200 \) N/mm, or (and) with fractured hard inclusions with density to 1% | 0–52 |
|                                            | Seams with bands of argillite or (and) coaly argillite, or (and) siltstone with \( 200 < A_{\text{dir}} \leq 400 \) N/mm, or (and) with fractured hard inclusions with density more than 1%, or with unfractured and consolidated inclusions with density to 2.5% | 1–163 |
| 2                                          | Seams with bands of siltstone, limestone and sandstone with \( A_{\text{dir}} > 400 \) N/mm, or (and) unfractured hard inclusions with density more than 2.5% and consolidated inclusions of any density | 4–523 |
| 3                                          |                                                        | 163 |

If a coal seam encloses dirt bands and inclusions, it should be placed in a group that describes more complex properties of one of the components. Typification of coal seams by the breakability category is given in table 4.

**Table 4. Typification of coal seams by breakability**

| Breakability category | Coal cuttability \( A_{\text{coal}} \) and brittleness \( B \) |
|-----------------------|-----------------------------------------------------|
| I                     | Viscous coal \( (B < 2.1) \) with \( A_{\text{coal}} < 150 \), or brittle coal with \( A_{\text{coal}} < 200 \) |
| II                    | Viscous coal with \( A_{\text{coal}} = 151–240 \), or brittle coal with \( A_{\text{coal}} = 201–300 \) |
| III                   | Viscous coal with \( A_{\text{coal}} > 240 \), or brittle coal with \( A_{\text{coal}} > 300 \) |

These typifications are the convenient tool for sound engineering decision-making on selection of coal mining equipment (in particular, cutters or rock-breaking tools), or for solving some technological tasks. In this case, the typification can be compiled into a classification matrix (table 5).
where each window describes a certain group of structural complexity and category of breakability, and can be assumed as a cumulative classification index.

### Table 5. Classification matrix of coal seam breakability

| Group of structural complexity of coal seams | Breakability category |
|--------------------------------------------|----------------------|
|                                           | I        | II        | III       |
| 1                                          | 1–I      | 1–II      | 1–III     |
| 2                                          | 2–I      | 2–II      | 2–III     |
| 3                                          | 3–I      | 3–II      | 3–III     |

#### 4. Discussion

To prove the validity of the proposed selection method of integral evaluation of breakability of coal seams we analyzed the dependencies of the overhaul life of screw cutterheads $R_{tbo}$ (Time Between Operations) on the following characteristics of coal seams: coal cuttability $A_{coal}$, which determines the overall load of cutters; generalized index of the contents and properties of the inhomogeneities in the seam $A_{inh}^{inh}$, which is a given characteristic of the resistance to cutting of rock layers and solid inclusions and describing the characteristics of dynamism (uneven) process of destruction of the coal seam; specific heterogeneity content in seam $S_{inh}^{inh} = S_{hard}^{inh} + S_{dir}$, reflecting, ceteris paribus, the frequency of peak loads that are responsible for breakdown failures of screw elements; abrasiveness of coal seam $\rho_{seam}$ affecting screw failure by wear; integral cuttability of coal seam $A_e$, which takes into account the indicators $A_{coal}$, $A_{inh}^{inh}$, and $S_{inh}^{inh}$.

Figure 4 represents the results of the analysis of the set of values for overhaul life $R_{tbo}$ of screw cutterhead with a diameter and working width of 800 mm equipped with picks. It shows that there is an explicit correlation of values for dependency $R_{tbo} = f(A_e)$ and also a lighter correlation in the dependency $R_{tbo} = f(A_{coal})$. However, there is an unacceptably high scatter for small values of $A_{coal}$ and $R_{tbo}$. Table 6 represents the results of statistical checking of significance for correlations between $R_{tbo}$ and $A_e$ and between $R_{tbo}$ and $A_{coal}$.
Figure 4. Dependencies of the overhaul life of screw cutterheads $R_{tho}$ on coal cuttability $A_{coal}$ (a), integral cuttability of coal seam $A_e$ (b), abrasiveness of coal seam $\rho_{seam}$ (c), generalized index of the...
contents and properties of the inhomogeneities in the seam $A_{inh}^*$ (d), and specific heterogeneity content in seam $S_{inh}^*$ (e)

Figure 4 and table 6 prove the validity of the choice of $A_e$ as a characteristic for the aggregate assessment of the cuttability of coal seams as objects destroyed by the cutters of the cutterheads of coal-mining machines.

Table 6. Results of statistical checking of significance for correlations between $R_{tbo}$ and $A_e$ and between $R_{tbo}$ and $A_{coal}$

| Dependency | Correlation index | Student’s criterion | Fisher’s criterion |
|------------|-------------------|---------------------|-------------------|
| $R_{tbo} = f(A_{coal})$ | 0.71 | 14.1 | 2.0 |
| $R_{tbo} = f(A_e)$ | 0.88 | 32.6 | 3.9 |

5. Conclusion
In the presented study, we conducted an analysis of indicators that characterize the property of coal seams. In the work, strength assessment was carried out using the integral cutting ability, which was presented as the sum of the cutting ability, density index and heterogeneity of the medium. The study analyzed the Russian experience in assessing the hardness of formations and proposed an empirical expression to evaluate the strength and hardness of coal seams.

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