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Invariant Classification of Rocks by Rock Drilling Resistance (Procedure)

由岩石钻进过程阻力得来的岩石不变量分类

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Abstract - **A great drawback of the existing classifications of rocks by the rock drilling resistance is their dependence on drilling equipment characteristics. The proposed method of rock classification makes no use of the data on rates (rpm) or time (min/m) of drilling by a particular machine or a tool but rests on the information on the structure of a rock mass and physico-mechanical properties of types of rocks the rock mass is composed of. A drilled object, which is a rock mass, is identified by the dimensionless set of the properties and abrasiveness of rocks.**

The rock mass properties B are represented by the functional $B = f\{\varepsilon_1(\sigma),\ \varepsilon_2(\Delta),\ \varepsilon_3(w)\}$ **, where** σ **is the uniaxial compression limit;** Δ **is the characteristic of dimension of structural blocks in the rock mass; is the characteristic of the effect exerted by hydrophysical state of the rock mass on its strength; are dimensionality operators for rock properties, considering their influence on the rock drilling resistance. The functional B is constructed for every layer of rock types composing the rock mass and its weighted mean value is calculated afterwards.**

Potential abrasiveness of lithology layers in the rock mass is represented as the functional $A = \varphi\{\vartheta_1(d),\ \vartheta_2(\Phi),\ \vartheta_3(Sm),\ \vartheta_4(P), \vartheta_5(Sc),\ \vartheta_6(r)\}$ **, where** d and Φ **are the weighted mean dimension of a rock grain and the coefficient of its shape (roundness), respectively;** Sm **and** Sc **are the weighted mean hardness of minerals composing a rock, and the hardness of cement (detrital rocks) and glass (magmatic rocks);** P **is the porosity, %;** r **is the tensile strength;** ϑ_i **are dimensionality operators for rock properties, considering their influence on the rock abrasiveness in drilling.**

Using the geometrical scale with the common ratio $\sqrt{2}$ **, in the real value range of the functional** B**, we have obtained the rock mass classification by the rock mass strength characteristics, and in the real value range of the functional** A**—the rock mass classification by its abrasiveness. Cumulative values of strength and abrasiveness per classes of rocks are the dimensionless characteristic of the rock drilling resistance. The classification is independent of the drilling equipment performances and is invariant on that score.**

The authors compare the invariant classification of rocks by rock drilling resistance with the rock classifications by drilling rate that are in actual use in mining.

Keywords – **rocks, classifications by drilling, rock resistance, hardness, abrasiveness, physico-mechanical properties**

I. INTRODUCTION

Available classifications of rock drillability are greatly governed by drilling equipment characteristics. Understanding of this disadvantage conditions the search for new approaches to new classifications to be independent of the impact of technological tools. This paper focuses on **the development of a rock drillability classification based on the physico-mechanical properties of rocks.**

It follows from numerous experimental data generalization that the drilling tool penetration resistance of rocks depends on: (1) rock strength; (2) rock mass structure (jointing); and (3) rock abrasivity. The properties (1) and (2) describe the state of a rock mass. The strength of a rock (as a solid) is governed by its genesis, mineralogy, structure etc. Special influence is exerted on the rock mass strength by the hydrophysical environment in the rock mass.

The rock drillability evaluation meets the challenge of aggregate estimate of a set composed of properties stated in various units of measurement. As a way-out alternative, the present authors suggest dimensionless presentation of numerous mechanical properties on a canonical scale for their aggregate estimate later on. The basis for this suggestion is the uniformity of laws concerned with hierarchy of rock blocks in the structure of rock masses and the clustering of the strength properties of rocks [1].

II. ROCK MASS STRENGTH ASSESSMENT

2.1. HYDROPHYSICAL CONDITIONS AND ROCK MASS STRENGTH

Out of characteristics of hydrophysical environment, we will only analyze moisture. Theoretically, of interest is a relation of the type of $\sigma_w = f(W)$, where the rock mass moisture W ranges from a defined zero saturation (air-dried state) to overall saturation W_w ($0 \leqslant W \leqslant W_w$); σ_w is the limit strength of rocks at the moisture W. Weakening of rocks under influence of moisture is usually assessed using a coefficient of rock mass resistance to water, or water stability, K_w (introduced in [2]):

$$K_w = \sigma_w / \sigma_d; \ \sigma_w \leqslant \sigma_d, \quad 0 < K_w \leqslant 1,$$

where σ_d is the rock limit strength in the air-dried state.

The authors suggest to account for the influence of hydrophysical conditions on the strength of hard rocks using the following relations:

$$\sigma_w \approx \sigma_d \cdot \exp(-W/P \cdot \lambda), \ K_w = \sigma_w/\sigma_d = \exp(-W/P \cdot \lambda), \tag{1}$$

where P is the porosity of rocks, %; σ_w is the strength of rocks at the moisture W, MPa; λ is a coefficient of yet unclear nature.

The ratio W/P in (1) is a characteristic of occupation of pores with water ($W/P \leqslant 1$). Evidently, when $W = 0$ (ideal dry rock), $W/P \cdot \lambda = 0$ and, accordingly, $\exp(-W/P \cdot \lambda) = 1$, $\sigma_w = \sigma_d$, $K_w = 1$ for any P and λ. When rocks are in the condition of overall saturation with water, K_w is governed by the material constitution of rocks and by W/P. For this reason, (1) has the coefficient λ. Presumably λ is in a certain manner exposed to the Rebinder effect, which needs validation, so, the expressions (1) are hypothetical and require respective proof. Some of the deductions are obtained on the static level, by the experimental data on uniaxial strength of rocks in dry and water-saturated state.

It is supposed that λ in (1) can be presented as a functional connection $\lambda = f(x1, x2)$, where x1, x2 are basic properties of material constitution of rock and fluid, respectively. For lack of data, λ is estimated using statistical calculation [3] where for each kind of rocks the moisture W, porosity P and wet rock strength σ_w are known. From (1), for $\lambda = 1$, we calculate initial approximation for the wet rock strength σ_{wc}. The calculated σ_{wc} is compared with the experimentally obtained values of the wet rock strength σ_{we}. On condition that:

$$\delta = (1 - \sigma_{wc} / \sigma_{we}) < (0.1), \tag{2}$$

it is assumed that λ is equal to 1. If the condition (2) is not fulfilled, we vary λ until (2) holds true and note the so-found value of λ. All in all, 80 kinds of rocks have been analyzed, with the found range of λ as follows: $0.1 < \lambda \leq 1.8$. It has been specified that $\lambda = 1$ for 36 kinds of rocks;

$\lambda < 1$—for 37 kinds of rocks; $\lambda > 1$—for 7 kinds of rocks.

According to the analysis of the calculation results, the values of K_w found from (1) are independent of the values of wet and dry rock strengths, σ_w and σ_d, respectively: K_w may have the same value for different σ_w and σ_d. From the calculation results:

$$K_w = \sigma_w / \sigma_d = 0.89 \approx 69/78 \approx 118/133 \approx 107/120 \approx 121/136 \approx 44/50 \approx \exp(-W/P \cdot \lambda).$$

Such equalities exist for different genesis rocks. Sticking to standardized terminology [2], the water stability coefficient K_w is of deeper meaning. Apparently, $K_w = \exp(-W_i/P_i \cdot \lambda_i)$ is not correlated with the strengths of rocks but relates with the ratio of strengths. Conceptually, K_w characterizes ability of rocks to "weaken" structural bonds at a microlevel under water saturation. The degree of "weakening" may differ in rocks of different material constitution. This phenomenon seems to be of interest and needs further consideration.

Based on the analysis and calculation, we conclude that the hypothetic premise formally presented in (2) is well applicable to predictive estimation of influence exerted by moisture and porosity on strength in rocks. It is found that for real rock masses (in particular, in Kuzbass), K_w is represented by the fourth order canonical scale:

$$K_w = K_{\text{ref}} \left(\sqrt[4]{2}\right)^{J-1}, \ J = 1, 2, 3, \ldots, r, \tag{3}$$

where $K_{\text{ref}} = 0.3$ is the minimum reference value of the water stability coefficient. Calculating J from (3) at $K_{\text{ref}} = 0.3$ and accounting for (1) yields:

$$J_h \approx 5.77 \cdot \text{Ln}(Kw) + 7.95 = 5.77 \cdot \text{Ln}(\exp(-Wz/Pz \cdot \lambda)) + 7.95, \tag{4}$$

where W_z and P_z are the weighted means of the natural moisture and porosity through borehole section; J_h is the class of hydrophysical condition of a rock.

2.2. JOINTING AND ROCK MASS STRENGTH

Jointing of a rock mass (rock mass block structure) is a very important characteristic of the rock mass state under blasting or drilling. As a measure of a rock mass jointing, we chose an in situ rock block size Δ (cm). By analogy with the linear scale of the rock mass classification by block structure, we represent Δ on the second order canonical scale:

$$\Delta_j = \Delta_0 \cdot \left(\sqrt{2}\right)^{J-1},$$

where Δ_0 is the reference size of an in situ rock block. From the above expression, calculate the class of rock mass jointing:

$$J_j = 2.8854 \cdot \ln\left(\frac{\Delta}{\Delta_0}\right) + 1 \tag{5}$$

Assuming $\Delta_0 = 9$ cm in (5), obtain:

$$J_j \approx 2.8854 \cdot \text{Ln}(\Delta) - 5.33, \ 9 \leq \Delta \leq 150 \text{ cm} \tag{6}$$

The range of the natural block size in a rock mass depending on the class of jointing is found:

$$6.36 \cdot \exp(0.3466 \cdot J_j) \leq \Delta \leq 9.0 \cdot \exp(0.3466 \cdot J_j).$$

2.3. ROCK MASS STRENGTH

Selecting a type and dimension of a bit, or a drilling regime is based on empirical relations including strength characteristics of rocks, such as hardness factor f; uniaxial compression σ_{com}; shearing strength σ_{shear}; contact strength σ_{cont}; indentation strength σ_{ind}; drilling strength σ_{drill}. These characteristics are also correlated. Therefore, for consistency, the characteristic of rock strength is accepted the uniaxial compression of dry rock, σ_d. Using:

$\sigma_d = \sigma_0 \cdot \left(\sqrt{2}\right)^{j-1}$ and $\sigma_w = \sigma_d \cdot K_w$ at $\sigma_0 = 5.5$ MPa,

obtain:

$$J_\sigma = 2.8854 \cdot \left[\ln(\sigma_d) - \ln(K_w)\ \right] - 3.92\ . \tag{7}$$

2.4. COLLECTIVE ESTIMATE OFR MASS CONDITION BY STRENGTH FACTORS

The collective estimate is summing of (4), (6) and (7):

$$F_{str} = J_h + J_j + J_\sigma\ , \tag{8}$$

where F_{est} is the dimensionless rock mass condition.
After appropriate transformations:

$$F_{str} \approx 2.8854 \cdot [\ln(K_w) + \ln(\Delta) + \ln(\sigma_d)] - 1.3. \tag{9}$$

Placing minimum values ($K_w = 0.3$; $\Delta = 9$; $\sigma_d = 5.5$) and maximum values ($K_w = 1$; $\Delta = 150$; $\sigma_d = 350$) in (9) brings to $F_{str\ min} = 6.5$ and $F_{str\ max} = 30$. Based on that, it is accepted that the dimensionless rock mass condition in terms of strength varies from 6 to 30. This range governs the representation of Fstr by the second order canonical scale with base-2 and reference value $F_{str} = 6$. Quantization of the scale is bounded by a sequence number J_s, at which Fstr from (9) becomes ≥ 30. The quantization results are shown in Fig. 1 as the curves $J_s = f(F_{str})$ that illustrate the offered rock classification by strength. The ranges of Fstr and J_s are:

$4.24 \cdot \exp(0.3466 \cdot J_s) \leqslant F_{str} \leqslant 6 \cdot \exp(0.3466 \cdot J_s)$;
$[2.8854 \cdot \ln(F_{str}) - 5.17] \leqslant J_s \leqslant [2.8854 \cdot \ln(F_{str}) - 4.17]$.

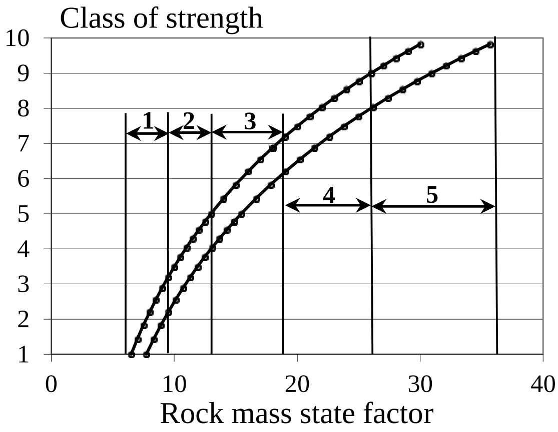


Fig.1. Rock mass classification by strength: 1—very weak rocks; 2—weak rocks; 3—medium strength rocks; 4—strong rocks; 5—very strong rocks

III. ROCK ABRASIVITY ESTIMATE BY PHYSICO-MECHANICAL PROPERTIES

To estimate resistance of rocks to drilling, we need to know the rock strength and another very important property that is the rock influence on the drilling tool wear, i.e. the rock abrasivity. This property is not a simple technological characteristic as compared to compression, tension etc. There are a lot of indirect methods for estimating rock abrasivity based on wear of an indenter made of various materials. Incommensurability of the results obtained with these methods impels the present authors to develop an abrasivity estimation procedure based on a set of physico-mechanical properties of rocks.

As the backbone characteristics of rock abrasivity, we select the shape and size of a grain; hardness of a rock-forming mineral and the mineral in whole, bond of grains, and moisture.

We omit description of the influence exerted by the above-listed characteristics on abrasivity of rocks (a more detailed information can be found in [4–10]) and only give the formal description of these characteristics required for the aggregate estimate of rock abrasivity.

3.1. SIZE AND SHAPE OF GRAINS, HARDNESS OF ROCK-FORMING MINERALS

On a canonical scale these characteristics are collection-wise presented in the relation:

$$\Psi_Z = \left[2.8854 \cdot \ln\left(\frac{D \cdot k_1}{d_0}\right) + 1\right] \cdot s_1; \tag{10}$$

$$s_1 = 0.022 \cdot \exp(0.5465 \cdot R_M), \tag{11}$$

where D and d_0 are the average mean size of a mineral grain and its references value, respectively, mm; k_1 is a coefficient accounting for the grain shape; s_1 is a relative measure of influence exerted by grains of certain hardness on rock abrasivity; R_M is the average mean hardness of rock-forming mineral. So, hardness of the mineral portion of a rock is:

$$R_M = 0.01 \sum_i M_i R_i\ \ ,$$

where M_i and R_i are an i-th mineral content of the rock (%) and the Mohs hardness, respectively.

The values of k_1 (10) are $k_1 = 1$ for roundish grains and $k_1 = 1.3$ for angular grains, given the grains are comparatively equal in size. By taking that this relationship is linear, we have: $k_1 = 1$ for well-rounded grains; $k_1 = 1.11$ for rounded grains; $k_1 = 1.18$ for half-rounded grains; $k_1 = 1.25$ for half-angular grains; $k_1 = 1.30$ for angular grains.

Concerning the reference size d_0 in (10), according to [11], grains with minimum size (0.005–0.05 mm) are typical of chemical rocks. On the assumption that grains smaller than 0.05 mm slightly affect abrasivity of rocks, we accept $d_0 = 0.05$ mm. Insert this value in (9) and obtain the granularity factor of rock abrasivity:

$\Psi_G \approx [2.8854 \cdot \ln(D \cdot k_1) + 9.64] \cdot s_1;$

$$0.05 \le D \le 8; \quad 1.0 \le k_1 \le 1.3. \qquad (12)$$

3.2. POROSITY AND HARDNESS OF BINDING MATERIAL

Equally in magmatic and sedimentary rocks, pore "surface" may be composed of a material which has either close properties to the properties of the rock grains (crystal), or these properties differ considerably. In the material abrasive tools are made of, the hardness of grains is always higher than the binding material hardness. However, in rocks this relationship is not always well-formed. In sedimentary rocks the roughness and hardness of pore surface is greatly influenced by a cement type (in abrasive tool, a binding material type). In magmatic rocks pores are formed in a non-decrystallyzed material that influences the roughness and hardness of the pores surface, too. The genesis of voidage (no matter pores or fractures) is not important. What important is the hardness of the pore surface.

The porosity factor Ψ_P of rock abrasivity is presented on the canonical scale as follows:

$$\Psi_P = \left(1 - 2.8854 \cdot \ln\left(\frac{P_i}{p_0}\right)\right) \cdot s_2, \qquad (13)$$

where P_i and p0 are, respectively, the porosity of a rock and the porosity reference value, %; s_2 takes into account the effect of the binding material hardness on the rock abrasivity.

With the accepted range of P_i from 0.2 to 25% and $p_0 = 25$, and using (13), we obtain:

$$\Psi_P \approx [-2.8854 \cdot \ln(P_i) + 10.29] \cdot s_2 \qquad (14)$$

The coefficient s_2 is relative but, unlike s_1 introduced in (11), has the other meaning content: s_2 illustrates relative influence of microhardness of the binding material on rock abrasivity rather than the relative hardness of the rock-forming mineral. The values of s_2 are found from test data on the binding material (cement, glass) microhardness. We make use of ratios of the Mohs microhardness and microhardness found on the PMT-3 microhardness measurement device. We are interested in not the absolute but relative values of hardness, i.e. s_2. The following results were obtained: the PMT-3 measurement microhardness:

$$s_2 = 8.9 \cdot 10^{-5} \cdot T_{PMT\text{-}3},$$

the Mohs hardness:

$$s_2 \approx 2.32 \cdot 10^{-3} \cdot (R_M)^{3.12},$$

where $T_{PMT\text{-}3}$ is the microhardness measured using the PMT-3 device; R_M is the Mohs hardness.

3.3. BONDING STRENGTH OF GRAINS

The influence of the grain bonding strength on rock abrasivity is poorly studied and for sedimentary rocks it is hypothetically based on the strength of a cement. With the strong cement, each grain at its place abrades a cutting tool until the grain is detached and removed from the tool and rock interaction zone. Hence it appears that with the stronger cement, the rock abrasivity increases. This statement is valid for crystal rocks, as well. With the weak bonding strength of grains, abravise refresh gets intensified. The bonding strength of grains is estimated in terms of ultimate tension σ_t (MPa). Assume that rock abrasivity grows with increasing σ_t, then the grain bonding strength factor Ψ_B is:

$$\Psi_B = \left[2.8854 \cdot \ln\left(\frac{\sigma_t}{\sigma_{0t}}\right) + 1\right] \cdot K_w \qquad (15)$$

where σ_t is the ultimate tension of dry rock, MPa.

Let the reference value be $\sigma_{0t} = 0.312$ MP, that is typical of weak hard rocks. Placing this value in (15) and appropriate transformation yields:

$$\Psi_B \approx [2.8854 \cdot \ln(\sigma_t) + 4.36] \cdot K_w, \; 0.312 \le \sigma_t \le 40. \qquad (16)$$

The bonding strength of grains is affected by rock moisture content, especially in sedimentary rocks. The quantitative estimates of the moisture and abrasivity relationship in rocks are given in [9], where it is shown that abrasivity of water-saturated rocks decreases greatly (to 30%). This effect is included in (15) in terms of the water resistance coefficient K_w discussed above in this article.

3.4. AGGREGATE ABRASIVITY OF ROCKS BY THE COLLECTIVE PHYSICO-MECHANICAL PROPERTIES. CLASSIFICATION

The framework of the rock abrasivity estimate is the set of (12), (14) and (16):

$$\breve{A} = \Psi_G + \Psi_P + \Psi_B,$$

where $\breve{A}$ is the abrasivity of a rock in conventional dimensionless units.

$$\breve{A} \approx 2.8854 \cdot \{\ln(D \cdot k_1) \cdot s_1 - \ln(P) \cdot s_2 + \ln(\sigma_t) \cdot K_w\} +$$

$$9.64 \cdot s_1 + 10.29 \cdot s_2 + 4.36 \cdot K_w. \qquad (17)$$

The estimate (17) characterizes abrasivity of rocks depending on the rock's physico-mechanical properties. In the conventionally measured abrasive wearing capacity of indenters, abrasivity has unit measures but they are relative, and are only used in classifications the objective of which is to refer this or that type of rocks to a suitable class of abrasivity. It's the abrasivity classes which are of importance in selecting a rock-cutting or rock-drilling tool, and not their quantitative evaluations.

With the accepted minimum values (D = 0.05 mm; $k_1 = 1$; $s_1 = 0.065$; P = 0.2%; $s_2 = 0.02$; $\sigma_t = 0.312$ MPa) and maximum values (D=10 mm; $k_1 = 1.3$; $s_1 = 1$; P = 25%; $s_2 = 1$; $\sigma_t = 40$ MPa) of the parameters included in (17), we obtain the range of $\breve{A}$: $\breve{A}_{min} = 3.2$; $\breve{A}_{max} = 63$. Quantification of $\breve{A}$ within this range is represented as the second order canonical scale, on the assumption that $\breve{A}_0 = \breve{A}_{min} = 3.0$:

$$\breve{A}_J = \breve{A}_0 \cdot \left(\sqrt{2}\right)^{J_a - 1}, \; J = 1, \ldots, 9, \qquad (18)$$

Table 1. Classifications of rocks by abrasivity.

Abrasivity class	Aggregate abrasivity, conventional units (range)	Abrasivity by [12]		Characteristic of rocks
		Initial scale	Canonical scale	
1	2	3	4	
1	3.0–4.2	<5	4.0–5.7	Very low abrasivity
2	4.2–6.0	5–10	5.7–8.0	Low abrasivity
3	6.0–8.5	10–18	8.0–11.0	
4	8.5–12.0	18–30	11.0–16.0	Subaverage abrasivity
5	12.0–17.0	30–45	16.0–23.0	Average abrasivity
6	17.0–24.0	45–65	32.0–45.0	Above-average abrasivity
7	24.0–34.0	65–90	45.0–64.0	Increased abrasivity
8	34.0–48.0	>90	64.0–91.0	High abrasivity
9	48.0–68.0		>91.0	Extremely high abrasivity

Table 2. Rock classification by drilling resistance

Rock mass strength factor (F_{str} by (9))				
6–9	9–13	13–18	18–26	26–37
Rock strength classes				
1–2	2–3	3–4	4–5	5–6

Rock abrasivity factor (A by (17))								
3–4	4–6	6–9	9–12	12–17	17–24	24–34	34–48	48–67
Rock abrasivity class (J_a by (19))								
1–2	2–3	3–4	4–5	5–6	6–7	7–8	8–9	9–10

Aggregate rock drilling resistance (F_{str} + A by (21))							
8–12	12–17	17–24	24–34	34–48	48–67	67–95	95–135
Rock drilling resistance classes							
0–1	1–2	2–3	3–4	4–5	5–6	6–7	7–8

where J_a is the class of abrasive capacity of the rock.

The results of the calculations by (18) are compared with the rock abrasivity classification by Baron and Kuznetsov [12] in Table 1.

By the data from the second column in Table 2, we obtain the abrasivity ranges within a class:

$$2.12 \cdot \exp(0.3466 \cdot J_a) \leq \breve{A} \leq 3 \cdot \exp(0.3466 \cdot J_a),\ J_a=1,...,9. \quad (19)$$

It follows from (19) that:

$$2.8854 \cdot \ln(\breve{A}) - 3.17 \leq J_a \leq 2.8854 \cdot \ln(\breve{A})+2.17.$$

The side-by-side comparison of the calculations by (19) and the data of the Baron and Kuznetsov classification (column 4 in Table 1) is possible using the plots in Fig. 2a, with the pre-found:

$$2.1 \cdot \exp(0.496 \cdot Y) \leq B \leq 4.12 \cdot \exp(0.45 \cdot Y);\ Y=1 \div 7, \quad (20)$$

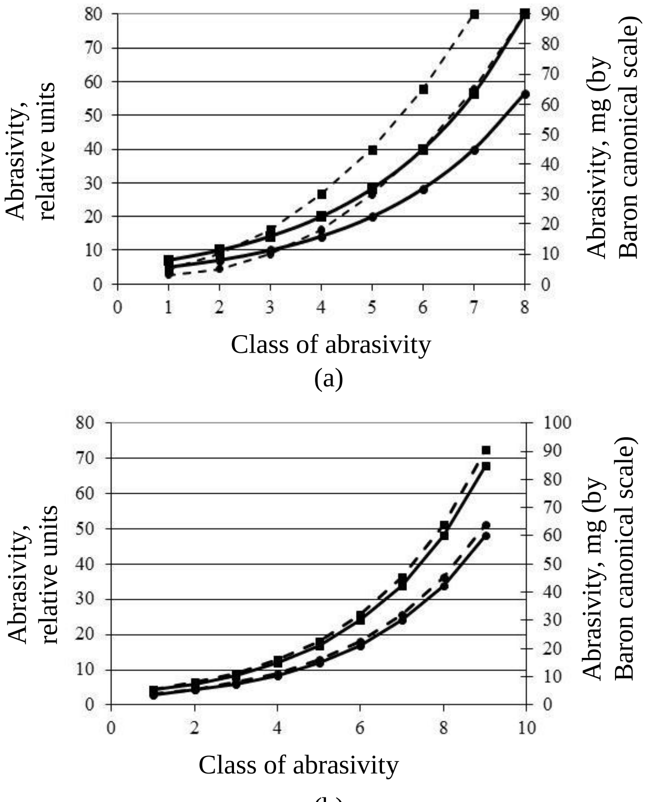
where B and Y are, respectively, the value of abrasivity index (wear of indenter, mg) and the class of abrasivity by Baron and Kuznetsov.

From the comparison of (19) with (20), the abrasivity indexes in both classifications exponentially depend on their classes though have different units of measurement and different amount of classes. The difference of the coefficients attached to the exponents in (19) and (20) is conditioned by different approaches to ranging the classification indexes in classes. As for the difference of the coefficients in front of the exponents in (19) and (20), this is because of the different units of measurement used in the classifications.

For the purpose of comparison, we present the classification by Baron and Kuznetsov on the canonical scale with the chosen reference value B = 3 mg (Fig. 2b).

The classifications are fairly close, and we can relate the aggregate rock abrasivity index obtained based on physico-mechanical properties of rocks, Ă, with the rock abrasivity based on steel indenter wear by the Baron and Kuznetsov method, B:

$$2.89 \cdot \breve{A} - 6 \leq B \leq 2.75 \cdot \breve{A} - 4.46.$$



(a) (b)

Fig. 2. Classifications of rocks by abrasivity: (a) classification by abrasivity (solid lines) versus the classification by indenter wear (dashed lines); (b) classification by abrasivity (solid lines) versus the classification by indenter wear on canonical scale (dashed lines).

We have compared the proposed method of rock abrasivity assessment by the aggregate physico-mechanical properties of rocks with the method of rock abrasivity assessment by Baron and Kuznetsov because the latter is widely used in mining industry.

The idea to apply aggregate physico-mechanical properties of rocks for estimating rock abrasivity appeared productive. This is confirmed by the fact of coherence of the classifications of rocks by abrasivity based on their physico-mechanical properties and based on steel indenter wear.

IV. CLASSIFICATION OF ROCKS BY DRILLING RESISTANCE

Rock drilling resistance Є is found as $Є = F_{str} + Â$, , i.e., we sum up the right-hand sides of (9) and (17) and, after transformations, have:

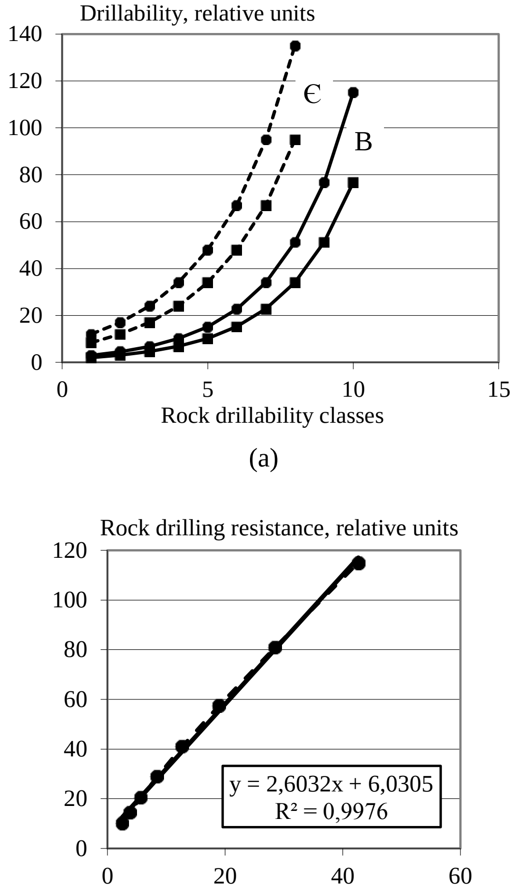
$$Є = 2.8854\cdot\{\ln(K_w) + \ln(\Delta) + \ln(\sigma_d) + \ln(D\cdot k_1)\cdot s_1 - \ln(P)\cdot s_2 + \ln(\sigma_t)\cdot K_w\} + 9.64\cdot s_1 + 10.29\cdot s_2 + 4.36\cdot K_w - 1.3$$

$$\ln(\sigma_t)\cdot K_w\} + 9.64\cdot s_1+10.29\cdot s_2+4.36\cdot K_w -1.3. \qquad (21)$$

With the minimum and maximum values of the parameters in (9) and (17), we obtain from (21) that Є falls in the following range: $8.4 \le Є \ge 95$, accounting for rounding off. Based on that we set a clustering procedure for Є in the canonical series with the denominator. The results of clustering Є on the canonical scale are given in Table 2 that is the classification of rocks by drilling resistance based on physico-mechanical properties rocks. Using the data from Table 2, we have related the rock drilling resistance index Є and J_σ :

$$5.93\cdot\exp(0.3466\cdot J_\sigma) \le Є \le 8.4\cdot\exp(0.3466\cdot J_\sigma);$$
$$\{2.8854\cdot\ln(Є) - 6.14\} \le J_\sigma \le \{2.8854\cdot\ln(Є) - 5.14\}.$$
$$J_\sigma = 1,\dots, 8.$$

From the comparison of the proposed classification of rocks by drilling resistance and the rock drillability classification suggested by the Central Research Institute for Geological Exploration in Figure 3, it is evident that the classifications are equitype.



(a) (b)

Fig. 3. Comparison of the rock drilling resistance classification based on aggregate physico-mechanical properties (Є) with the rock drillability classification offered by the Central Research Institute for Geological Exploration (D).

The deduction above is confirmed by the functional relationship Є = f(D) with the correlation ratio $R^2 = 0.99$ in Figure 3b. The method of estimation of rock drilling resistance by the aggregate of physico-mechanical properties of rocks offered in this article is quite appropriate to describe the essence of drilling.

V. CONCLUSION

The authors have proposed the new method of rock classification by drilling resistance, that is invariant regarding drilling equipment and uses borehole drilling data on physico-mechanical properties of rocks.

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