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A new method to test rock abrasiveness based on physico-mechanical and structural properties of rocks

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ABSTRACT

A new method to test rock abrasiveness is proposed based upon the dependence of rock abrasiveness on their structural and physico-mechanical properties. The article describes the procedure of presentation of properties that govern rock abrasiveness on a canonical scale by dimensionless components, and the integrated estimation of the properties by a generalized index. The obtained results are compared with the known classifications of rock abrasiveness.

1. Introduction

In Russia, intensive studies of rock abrasivity issues date back to the 1950s–1980s, resulting in the development of dozens of experimental methods for rock abrasivity evaluation. All of them were based on the same principle, i.e. abrasion (wear) of different indenters, such as cutting heads, disks, steel rings, rods, needles, shot, in contact with rocks (Baron and Kuznetsov, 1961; Karpov, 1962; Lyubimov, 1967; Golubintsev, 1968; Khruschev and Babichev, 1970; Spivak, 1972; Vozdvizhensky et al., 1973; Abramson et al., 1985; Artsimovich, 1985; Kalinin et al., 2000). In search of the quantitative assessment of the rock abrasivity, the researchers studied the regularities of the indenter wear disregarding the quantitative evaluation of rock physico-mechanical properties.

In analogy with European practice, every method was provided with specific abrasivity classifications, which appear incommensurable or inconsistent with those obtained by other methods. For example, the vein quart is classified as a medium-abrasive rock in Baron and Kuznetsov (1961) and as a high-abrasive rock in Lyubimov (1967). These classifications are characterized with the specific feature, i.e. the abrasivity magnitude is related to the rock name, disregarding measurement units. Rocks, termed by the same name, are used to differ in physico-mechanical properties and abrasivity as well. Nevertheless, the scientists manage to derive correlations between different classifications in terms of comparison of rock names, though it is incorrect.

In the specific cases (Spivak, 1972), the empirical (linear) equations were derived to evaluate the indenter wear resistance in terms of grain size, rock hardness, and porosity. Moreover, it is demonstrated that the compressive force or rotation velocity applied to an indenter crucially affects not only the magnitude but also the sign of coefficients in equations.

European scientists described Schimazek's process (F_{schim}) for rock abrasivity evaluation without laboratory tests of the indenter wear resistance, where the corrected hardness, tensile strength and quarts grain size were considered (Schimazek and Knatz, 1970; Brown, 1981; Ewendt, 1989):

$$F_{\mathrm{schim}} = 10^{-2}\sigma_{\mathrm{b}} d_{\mathrm{Qu}} V_{\mathrm{Qu}} \tag{1}$$

where d_{Qu} is the average grain size of quarts (mm), σ_{b} is the ultimate tensile strength evaluated by Brazil test method (MPa), and V_{Qu} is the rock hardness correlated to quarts hardness (%).

The parameter F_{schim} is empirically obtained. From Eq. (1), $F_{\mathrm{schim}} = 0$ is used for the quarts-free rocks because we have $d_{\mathrm{Qu}} = 0$. However, the abrasivity does not depend only on quarts, it is also affected by other minerals. Given that $d_{\mathrm{Qu}} = 0$, a grain size value is considered to be "fictitious", at which it is conventionally assumed that $d_{\mathrm{Qu}} = 0.025$ mm. If $d_{\mathrm{Qu}} > 1$ mm, it is proposed to evaluate the abrasivity index by CERCHAR test (scratching method). The index σ_{b} in Eq. (1) is an intergrain bonding force.

The recognition of the significance of the rock abrasivity problem helps to adopt "standard" methods for the ground, mainly distinguishing their simplicity and specific validity. In Russia, the conventional standard methods involve the abrasion of lead-shot

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for disintegrated rocks (Lyubimov, 1967) and abrasion of a silver-steel indenter (a longitudinally holed rod) for intact rocks (Baron and Kuznetsov, 1961). The adoption of these methods with well-known imperfections was mandatory because of the urgent need in an instrument enabling to correlate respective parameters.

In view of the above analyses, we conclude that:

(1) In spite of many years of research work conducted by the scientists worldwide, there are no evidences to state that we have gained the complete solution to the rock abrasivity evaluation problem. None of modern laboratory test procedures for rock abrasivity assessment can be considered as a perfect one, as the test results are relative and classification systems are incommensurable, because they are structured in terms of rock names, disregarding the physico-mechanical properties of rocks.

(2) Any of available test methods can be recommended as a claimer for International Society for Rock Mechanics (ISMR) Standard under the rigorous postulation of force impact limits (load on a rock specimen, velocity, etc.) on indenters as the main regulatory indices.

(3) It is evident that the main reason for the incomparability of the rock abrasivity results is the lack of the unified procedure for estimating the basic physico-mechanical properties of rocks, impacting the potential rock abrasivity, rather than the lack of a standard test method. This cumulative quantitative index for rock properties would make it possible to express the abrasivity evaluated by any method in terms of a system of physico-mechanical properties of a tested specimen, rather than in terms of rock name, and to eliminate incorrect relationships between the rock abrasivity classifications based on different methods.

Hereinafter the authors explicate the new-developed method for the evaluation of rock structural and physico-mechanical properties, affecting the rock abrasivity, as an aggregate quantitative index.

2. Quantitative evaluation of rock structural and physico-mechanical properties

2.1. General statement

The rock abrasivity assessment is directly related to the process performance and is intended to establish the optimal conditions for "rock-working organ of a machine" interaction. Material properties of this coupling tend to vary under thermodynamic effects induced by friction. The abrasivity of rock ($\ddot{A}$) determined by a combination of its structural and physico-mechanical properties can be expressed as $\ddot{A}=\varphi_1(Ç)$, where $Ç$ represents a rock type. The wear of working organ (R) depends on the properties of material ($Đ$) that it is made of, structural characteristics (L), and operation modes (G), i.e. $R=\varphi_2(Đ, L, G)$. The effective interaction of these solid bodies as a single system is possible under the condition $\ddot{A} \ll R$. Alternatively to the natural properties, the mechanical and structural characteristics of the working organ can be adjusted in terms of evaluated abrasive characteristics of rock ($\ddot{A}$). Disregarding the calculation of R as an individual actual problem, we focus on the procedure for assessment of uncontrollable module properties and their reduction to a common quantitative index $\ddot{A}=\varphi_1(Ç)$.

The main problem in evaluation of $\ddot{A}$ is the necessity to reduce a respective system of rock properties governing the rock abrasivity to a single quantitative index. As the rock properties are measured in different physical units, it is necessary to reduce the obtained rock properties to a dimensionless form in order to obtain a single index and then their aggregate presentation.

There are many publications mainly on the strength and stability of rock masses where issues of the dimensionless presentation of rock properties and their aggregate presentation were considered (Bieniawski, 1973; Shemyakin et al., 1992; Shupletsov, 2003; Aksoy, 2008). Bieniawski (1973) described the rock mass classification by CSIR system. In most cases, the evaluation of the aggregate index is reduced to the assessment of experts' scores, taking into account the share of every rock property impact on the process under consideration and summing up the final scores.

Alternatively to this statement, our approach is based on the regularies in clustering geomaterials according to their properties and structures. The authors managed to establish these regularities thanks to the scientific discovery (Shemyakin et al., 1992) and respective theoretical fundamentals of hierarchic classifications by rock properties (Oparin and Tanaino, 2009, 2011). The level of the property clustering by a character of the property impact on the rock abrasivity is estimated by one of the following formulas (Oparin and Tanaino, 2011):

$$J_X = 2.8854\ln\left(\frac{C_X}{R_{X0}}\right)+1 \quad (R_{X0}=C_{X\min}) \tag{2}$$

$$J_X = 1-2.8854\ln\left(\frac{C_X}{R_{X0}}\right) \quad (R_{X0}=C_{X\max}) \tag{3}$$

where J_X is the level of the property (X) clustering; C_X is the value of property X in conventional measurement units; R_{X0} is the basic value of property X; $C_{X\min}$, $C_{X\max}$ are the minimum and maximum values of property X in a rock class under estimation, respectively.

Eq. (2) is valid if the increase in the property value leads to the increase in its impact on the abrasivity, and Eq. (3) works in the alternative case. It follows from Eqs. (2) and (3) that they conceptually fulfill two concurrent operations: they determine a clustering level and transform the property value into a dimensionless form. A set of rock-specimen properties evaluated ($X = 1,2,\ldots,k$), i.e. its abrasivity, can be expressed as an algebraic sum:

$$\ddot{A}=\sum_{X=1}^{k}J_X$$

Thus, the authors set forth the fundamentals of the new approach to the rock abrasivity evaluation on the basis of physico-mechanical properties. Hereinafter, we identify the basic rock properties, constitutive relationship for the rock abrasivity, and represent them in a dimensionless form in a canonical scale.

2.2. Constitutive rock abrasivity properties and their reduction to a dimensionless form

We consider the basic properties characterizing the rock abrasivity: grain size and shape, hardness of mineral constituents, porosity, intergrain bonding force, and rock moisture content. As the mechanism for the effect of the above properties on abrasivity is described in details in Baron and Kuznetsov (1961), Karpov (1962), Golubintsev (1968), Spivak (1972), Vozdvizhensky et al. (1973), Abramson et al. (1985), and Kalinin et al. (2000), we focus on their formalized representation enabling to make the cumulative evaluation of the rock abrasivity.

2.2.1. Size and form of rock grains, and hardness of mineral constituents

These properties can be presented in the canonical scale as follows: