ГЕОМЕХАНИКА. РАЗРУШЕНИЕ ГОРНЫХ ПОРОД

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Studying physical and mechanical properties of rocks to carry out an express assessment of crushability parameters in the conditions of chrysotile asbestos rock mass

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Abstract

Introduction. *The solution of certain problems of geomechanics and geotechnology is increasingly demanding indirect express methods for rock mechanical properties assessment, including the methods using the Schmidt hammer. Schmidt hammer application does not require a specialized set of testing equipment and highly qualified personnel to maintain this equipment. Tests are carried out directly in the field.*

Research objective *is to estimate the possibility of using indirect express methods to determine the crushability indices and the path of least resistance.*

Methods of research. *The indicators estimation by indirect express methods is demonstrated through the serpentinite rocks of the Jitikara chrysotile-asbestos deposit which were submitted to the related field and laboratory tests. In local areas of the exposed rock, in the field environment, measurements were made with a Schmidt hammer according to the ASTM method. Rock samples were additionally tested for compressive strength in laboratory conditions using specialized press machines.*

Results. *Empirical dependences of the serpentinite rock crushability on the ultimate uniaxial compressive strength and the Schmidt hammer face rebound value were established. A comparative analysis was carried out with empirical dependencies established by other authors. A method for calculating the optimal path of least resistance for a blasting pattern is proposed based on the established dependencies.*

Conclusions. *Based on the results, it was found that the express method for assessing the crushability indices and the size of the path of least resistance using a Schmidt hammer is quite efficient and can be successfully applied for express assessment of physical and mechanical properties variability at Russian mining enterprises. However, it should be taken into account that Schmidt hammers cannot be used in certain mining and geological conditions without laboratory calibration of all devices planned for use.*

Keywords: *Schmidt hammer; ultimate compressive strength; rebound value; crushability; path of least resistance; serpentinite.*

Introduction. At all stages of field development, knowledge about the strength and deformation properties of rock building up the mine field is crucial since these particular indicators determine the technological solutions for successful mineral extraction.

Hard rock preparation by separating it from the main mass is usually carried out by drilling and blasting. The quality of rock mass preparation is determined by a number of indicators: boulder frequency, granulometric composition and the nature of rock mass disintegration after blast. The main quality coefficient is the output of oversized fractions in the blasted rock mass, i.e. the quality of rock mass crushing.

Crushing is widely used in minerals preparation for processing, their beneficiation, and in the production of building materials. Therefore, the characteristics of rock crushability are important in order to calculate the parameters of rock mass preparation by blasting, as well as to clarify the strength characteristics of rocks whose properties change with mining depth growth.

Crushability is rock resistance to crushing on exposure to a dynamic load. Crushability is determined by the energy estimation of the failure of rock which is in the state of a combined stress. There are six classes of crushability (Table 1).

Table 1. Classes of rock crushability
Таблица 1. Классы дробимости горных пород

Class	Rock characteristic	Crushability V_{max}, cm^3
I	Extremely hard to crush	Less than 1.8
II	Very hard to crush	1.8–2.7
III	Hard to crush	2.7–4.0
IV	Medium crushability	4.0–6.0
V	Fragile	6.0–9.0
VI	Very fragile	More than 9.0

Methods of research. At A. A. Skochinsky Institute of Mining, L. I. Baron, V. M. Kurbatov and R. V. Orlov developed a method for determining rock crushability through rock relative resistance to crushing under shock loading [1, 2]. Crushability is determined by the granulometric composition of the products of a 50–70 g sample destruction after a one-time drop of a 16 kg load on it from a height of 0.5 m. The crushability index (cm^3) is numerically equal to the volume of the fraction that passed through a screen with the holes of d_{max} = 7 mm, and is determined by the formula: $V_{max} = m_7/\rho$ where m_7 is the mass of the –7 mm fraction, g; ρ is the volumetric mass of rock, g/cm^3.

This approach is quite convenient in the field. However, one of the authors notes that data for one fraction are unreliable. A complete analysis of crushed rock granulometric composition increases the labor intensity of the research. A specific distribution of lumps of different sizes is a statistical realization of only one possible test result, which negatively affects the accuracy of the data obtained [3].

There are also methods for determining crushability, in which the pieces are subjected to pounding, abrasion, and crushing in closed vessels. Such tests are carried out in laboratory conditions using expensive press, measuring, and auxiliary equipment, therefore being rather labor and time intensive. The development of reasonable, effortless and efficient express methods for determining crushability directly in the field will increase the speed of obtaining and processing the data necessary to make and correct process decisions at a production site in time.

The solution of certain problems of geomechanics and geotechnology is increasingly demanding indirect express methods for rock mechanical properties assessment, including the methods using the Schmidt hammer. Schmidt hammer application does not require a specialized set of testing equipment and highly qualified personnel to maintain this equipment. Tests are carried out directly in the field. Due to its wide usage in rock mechanics, a non-destructive method for assessing marginal rock strength properties with a Schmidt hammer has been adopted by the International Society for Rock Mechanics (ISRM) and American Society for Testing and Materials (ASTM).

Unlike laboratory methods, the measurement result of the express method of rock mechanical characteristics determination is the Schmidt hammer face rebound value. To move from the rebound value *Hr* to mechanical characteristics, it is required to determine dependences between the determined properties and the *Hr* value in laboratory conditions with further calibration of the instrument (Schmidt hammer).

One of the main mechanical properties of rocks is the ultimate uniaxial compressive strength σ_{compr}, MPa [4–8]. The calibration of Schmidt hammers is traditionally performed for this characteristic specifically. Numerous empirical formulas described by linear, power, and exponential dependences are found in a number of national and foreign scientific works [9–24].

Table 2. Empirical dependencies of the ultimate strength in a sample and crushability on the Schmidt hammer face rebound value

Таблица 2. Эмпирические зависимости предела прочности в образце и дробимости от величины отскока молотка Шмидта

Author (year)	Type of rocks	Ultimate uniaxial compressive strength σ_{compr}, MPa	Crushability V_{max}, cm^3
Xu et al. (1990) [7]	Prasinites	$2{,}99\exp(0{,}06Hr)$	$\frac{435}{2{,}99\exp(0{,}06Hr)+9}$
	Serpentinites	$2{,}98\exp(0{,}063Hr)$	$\frac{435}{2{,}98\exp(0{,}063Hr)+9}$
	Gabbro	$3{,}78\exp(0{,}05Hr)$	$\frac{435}{3{,}78\exp(0{,}05Hr)+9}$
Karaman et al. (2015) [12]	Igneous rock	$0{,}097Hr^{1{,}88}$	$\frac{435}{0{,}097Hr^{188}+9}$
IM UB RAS, Kharisov T. F. et al. (2020) [18]	Serpentinites	$0{,}0017\exp(0{,}14Hr)+$ $+\ 0{,}3Hr+9-0{,}0017$	$\frac{435}{0{,}0017\exp(0{,}14Hr)+0{,}3Hr+9}$

It is known that the rock lumps resistance to disrupturing and crushing is determined by the tensile and compressive strength. O. G. Latyshev established the following empirical relationship between crushability and hardness of effusive rocks, which is expressed by the formula [25]:

$$V_{max} = \frac{10^3}{(23f + 21)}, \quad (1)$$

where f is the hardness coefficient according to M. M. Protodyakonov.

The correlation ratio η = 0.76 obtained for formula (1) indicates the statistical significance of the dependence.

It is also known that the hardness coefficient can be approximately calculated by the formula:

$$f = 0{,}1\sigma_{compr}. \quad (2)$$

Table 3. The results of determining the ultimate uniaxial compressive strength and the Schmidt hammer face rebound value in the serpentinites of the Jitikara chrysotile-asbestos deposit

Таблица 3. Результаты определения пределов прочности при сжатии и величины отскока молотка Шмидта в серпентинитах Джетыгаринского месторождения хризотил-асбеста

Parameter	Type of rock										Mean value	Coefficient of variation, %
	Appoperidotite serpentinite											
Hr	67,0	62,0	70,0	71,5	68,0	66,5	59,0	67,0	69,0	64,5	66,45	5,65
σ_{compr}	27,8	53,0	48,4	33,2	38,2	40,9	39,6	30,8	33,0	40,9	38,58	20,32
	Appodunite chrysotile-lizardite serpentinite											
Hr	68,0	56,5	70,5	58,0	63,0	62,0	66,5	59,0	55,5	61,5	62,05	8,1
σ_{compr}	20,2	30,7	29,5	22,0	29,9	22,8	24,5	29,1	27,6	28,7	26,50	14,27
	Appoperidotitis-lizardite serpentinite											
Hr	67,0	69,5	70,5	64,0	67,5	72,0	66,0	65,5	69,0	66,5	67,75	3,64
σ_{compr}	45,70	44,10	59,40	46,10	64,50	52,30	50,00	54,80	61,90	47,80	52,66	13,74
	Appodunite lizardite serpentinite											
Hr	49,0	52,5	53,0	62,5	51,0	39,0	42,0	42,0	58,5	55,0	50,45	15,03
σ_{compr}	20,6	5,9	24,0	21,0	21,7	15,9	20,9	22,7	18,1	20,0	19,08	27,01
	Lizardite asbestos-bearing serpentinite											
Hr	50,0	53,0	62,5	56,0	63,0	61,5	56,0	54,0	58,5	59,0	57,35	7,52
σ_{compr}	18,5	24,4	14,7	29,9	23,6	24,0	27,1	18,9	24,5	26,2	23,18	19,6
	Lizardite serpentinite											
Hr	56,00	63,00	63,50	71,50	65,00	70,50	65,00	61,00	73,50	73,50	66,25	8,78
σ_{compr}	52,30	45,80	48,70	74,60	52,80	48,00	55,60	45,90	39,10	39,30	50,21	20,17
	Lizardite talcose serpentinite											
Hr	64,0	67,5	75,5	60,5	63,5	68,0	70,0	59,0	62,5	60,5	65,10	7,87
σ_{compr}	24,4	33,2	32,4	39,1	36,0	33,8	32,1	32,6	29,9	30,6	32,41	11,91
	Appoperidotite chrysotile-lizardite serpentinite											
Hr	76,5	73,0	81,5	77,0	76,5	81,0	81,0	81,5	73,5	65,5	76,70	6,63
σ_{compr}	137,2	106,0	95,5	145,2	166,2	68,2	125,8	129,8	120,1	110,1	120,41	22,78

Thus, by combining formulae (1) and (2), it is possible to obtain the ultimate uniaxial compressive strength from the crushability index:

$$\sigma_{compr} = \frac{435}{V_{max}} - 9. \quad (3)$$

In 2020 [18], when studying the strength properties of serpentinites, a relationship was established between the compressive strength and Schmidt hammer rebound, expressed by the formula:

$$\sigma_{compr} = 0{,}0017\exp(0{,}14Hr) + 0{,}3Hr + 9 - 0{,}0017, \quad (4)$$

where Hr is the Schmidt hammer face rebound value.

So, by simultaneous solution of formulae (3) and (4), it is possible to obtain crushability for serpentinite rocks:

$$V_{max} = \frac{435}{0{,}0017\exp(0{,}14Hr) + 0{,}3Hr + 9}. \quad (5)$$

Meanwhile, there is a large number of established empirical relationships between the effusive rocks strength and the Schmidt hammer face rebound value [10–18]. By successively substituting formula (3) into the analyzed dependences of different authors, it is possible to express the crushability value V_{max} through the rebound value Hr (Table 2).

As applied to open pit mining, based on the obtained dependences (Table 2), it seems possible to calculate the optimal path of least resistance (PLR) for a blasting pattern through the Schmidt hammer face rebound value.

After analyzing the experience of blasting in open pits in different mining and geological conditions, it was found that the specific consumption of explosives q, which provides a given quality of crushing, correlates with sufficient reliability with the crushability index, which is expressed by the empirical formula [1]:

$$\sigma_{compr} = 0{,}678\exp\left(-0{,}065V_{max}\right). \quad (6)$$

The coefficient of variation in this case is 11.8%.

The specific consumption of explosives can be calculated using the following formula:

$$q = \frac{M}{V}, \quad (7)$$

where M is the mass of the explosive charge in the borehole, kg; V is the volume of blasted rocks, m^3.

The mass of the explosive charge is calculated based on the known expression:

$$M = \left(\frac{\pi d^2}{4}\right) l_{charge} \rho_{explosive}, \quad (8)$$

where d is the explosive charge diameter, m; l_{charge} is the length of the explosive charge, m; $\rho_{explosive}$ is the density of the explosive, kg/m^3; V is the volume of blasted rocks, m^3. V is calculated by the formula:

$$V = mW_0^2 L_{eff}, \qquad (9)$$

where m is the burden-to-spacing ratio; W_0 is the PLR size, m; L_{eff} is the effective length of the borehole; in open-pit mining, L_{eff} corresponds to the height of the bench, m.

By simultaneous solution of formulae (5)–(9), the dependence is obtained between the PLR size and the Schmidt hammer face rebound value for serpentinites of the Jitikara deposit:

$$W_0 = \sqrt{\frac{M}{0{,}678\exp\left(\dfrac{28{,}275}{0{,}0017\exp(0{,}14Hr) + 0{,}3Hr + 9}\right) mL_{eff}}}. \qquad (9)$$

It is obvious that if other empirical dependences (Table 2) are used instead of formula (5), PLR value can also be obtained for other lithotypes as well.

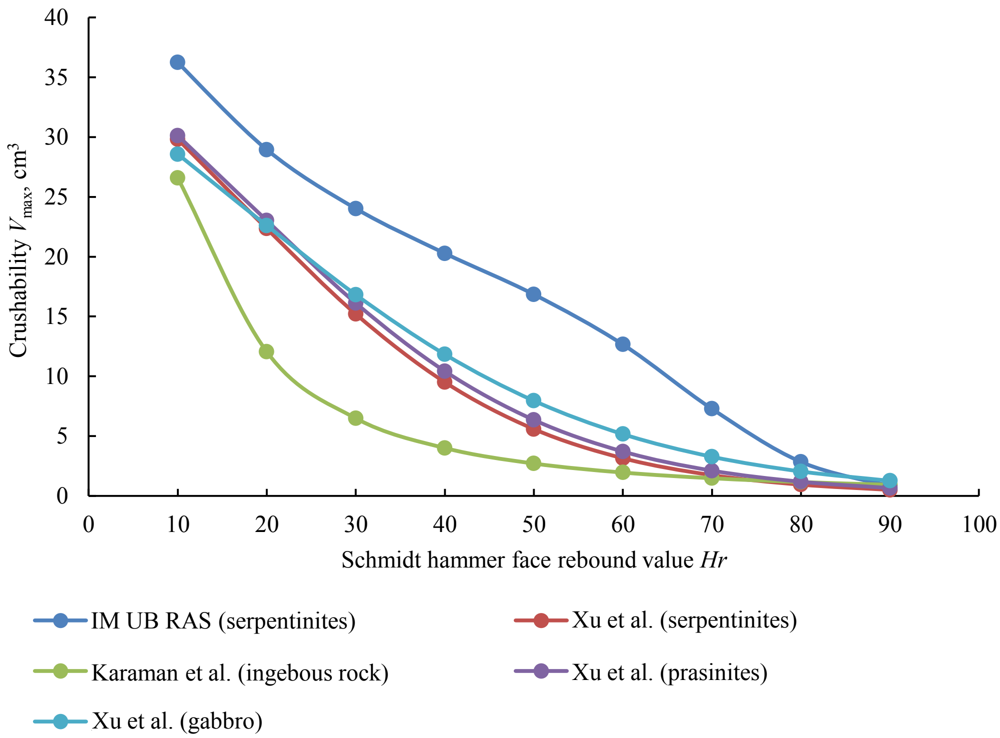

Figure 1. Dependences of rock crushability on the Schmidt hammer face rebound value
Рисунок 1. Зависимость дробимости пород от величины отскока бойка молотка Шмидта

Results. The possibility of the dependences practical application is considered on the example of serpentinite rocks of the Jitikara deposit.

At the deposit, in local areas of the exposed rock, in the field environment, measurements were made with a Schmidt hammer according to the ASTM method. Rock samples were additionally tested for compressive strength in laboratory conditions using specialized press machines (Table 3).

Based on the formulae given in Table 2, the dependences of rock crushability and PLR sizes on the Schmidt hammer face rebound value are plotted (Figures 1 and 2).

Comparative analysis of the dependencies makes it possible to make the following conclusions.

It follows from the graphs that both rock crushability and the PLR sizes vary in a fairly wide range even for the same lithotype (serpentinites, dependencies of IM UB RAS and Xu) when formulae obtained in this research and formulae obtained by other researchers are used in calculations (Table 2). These discrepancies are obviously determined both by the difference in the physical and mechanical properties of particular lithotypes in different deposits, and by different characteristics of the applied Schmidt hammers, which can be of two types: L and N.

However, the general trend in the dependences of crushability and PLR size on *Hr* remains for various lithotypes: gabbro, prasinites, igneous rocks, and serpentinites. With an increase in the the Schmidt hammer face rebound, the values of both V_{max} and W_0 decrease logarithmically and non-linearly.

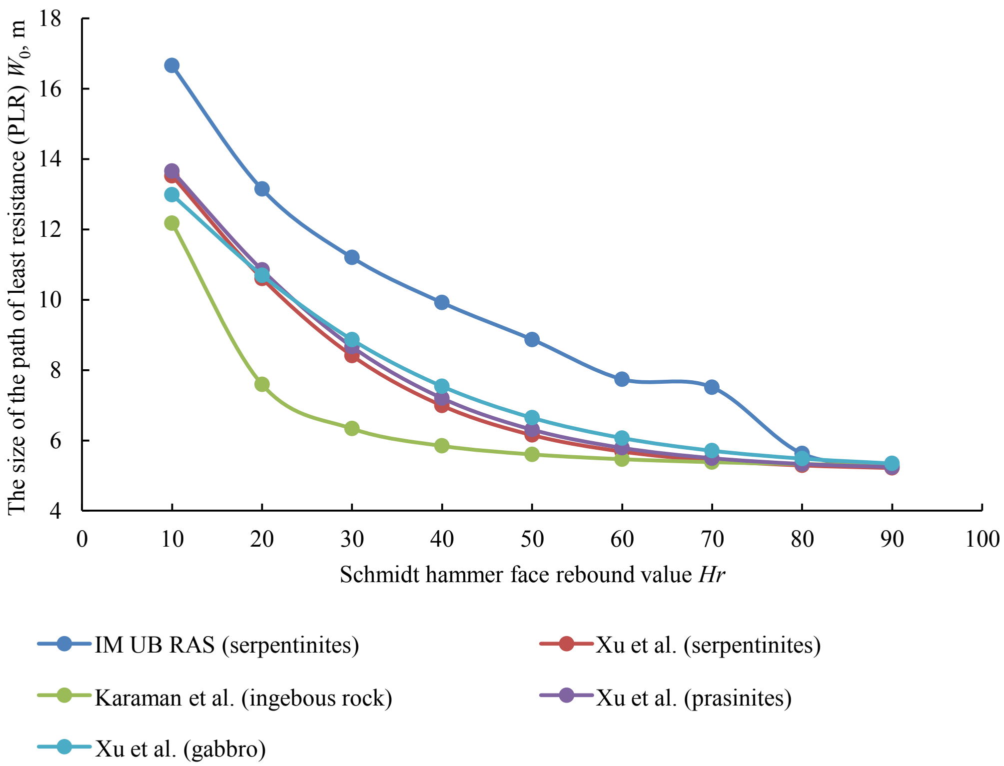

Figure 2. Dependence on the PLR size and the Schmidt hammer face rebound value
Рисунок 2. Зависимость величины линии наименьшего сопротивления от величины отскока бойка молотка Шмидта

So, with an increase in the rebound value from 10 to 40 (4 times), the crushability of serpenitinites changes (according to the IM UB RAS formula) from 37 to 4 cm^3, i.e., more than 9 times. A further increase in rebound does not lead to such a significant increase in crushability. As *Hr* increases from 40 to 90, V_{max} smoothly decreases from 4 to 1 cm^3.

When using an indirect assessment of rock crushability, an increased control of accuracy at low values of the Schmidt hammer face rebound (up to 40–60) can be recommended. With rebounds of 60 and more, field measurement errors will have a minor effect on the result of crushability and PLR determination.

It is therefore important to calibrate specific models of the Schmidt hammer in laboratory conditions for the rocks and lithotypes of the deposit where they are planned to be used.

Conclusions. Based on the research results, it can be concluded that the express method for assessing crushability indices and PLR size using a Schmidt hammer is quite effective and can be successfully used for express assessment of physical and mechanical properties variability at Russian mining enterprises.

However, it should be taken into account that Schmidt hammers cannot be used in certain mining and geological conditions without laboratory calibration of all devices planned for use. The accuracy of field measurements at small rebound values of the Schmidt hammer should also be considered, which is easily achieved by standard methods, i.e. increasing the number of measurements and carrying out their statistical processing.

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Исследование физико-механических свойств пород для экспресс-оценки параметров дробимости в условиях массива хризотил-асбеста

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Реферат

Введение. *При решении ряда задач геомеханики и геотехнологии все более актуальными и востребованными становятся непрямые (косвенные) экспресс-методы оценки механических свойств пород, в том числе с применением молотка Шмидта. При использовании молотка Шмидта не требуется специализированного комплекса испытательного оборудования и высококвалифицированного персонала по обслуживанию этого оборудования. Испытания проводятся непосредственно в полевых условиях.*

Цель работы. *В настоящей работе оценена возможность применения косвенных экспресс-методов при определении показателей дробимости и линии наименьшего сопротивления.*

Методология. *Оценка показателей косвенными экспресс-методами показана на примере серпентинитовых пород Джетыгаринского месторождения хризотил-асбеста, для которых были проведены соответствующие полевые и лабораторные испытания. На локальных участках обнаженного массива в полевых условиях производились измерения молотком Шмидта по методике ASTM. Дополнительно проводились испытания образцов горных пород на предел прочности при сжатии в лабораторных условиях с применением специализированного прессового оборудования.*

Результаты. *Установлены эмпирические зависимости дробимости серпентинитовых пород от предела прочности на одноосное сжатие и величины отскока бойка молотка Шмидта. Проведен сравнительный анализ с эмпирическими зависимостями,*

установленными другими авторами. Предложена методика расчета оптимальной линии наименьшего сопротивления для паспорта буровзрывных работ на базе установленных зависимостей.
Выводы. *На основании результатов установлено, что экспресс-метод оценки показателей дробимости и величины линии наименьшего сопротивления с применением молотка Шмидта является достаточно эффективным и может быть с успехом использован для экспресс-оценки изменчивости физико-механических свойств на российских горнодобывающих предприятиях. Однако следует учитывать, что нельзя использовать молоток Шмидта в конкретных горно-геологических условиях без лабораторной тарировки всех планируемых к использованию приборов.*

Ключевые слова: *молоток Шмидта; предел прочности на сжатие; величина отскока; дробимость; линия наименьшего сопротивления; серпентинит.*

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