Physical properties and fracture behavior of rocks in uniaxial and triaxial compression: A case-study of Zhdanovskoe deposit, Kola Mining and Metallurgical Company

AV Zemtsovsky*, NN Kuznetsov and AK Pak
Mining Institute, Kola Science Center, Russian Academy of Sciences, Apatity, Russia
E-mail: *zemtsovskiy@yandex.ru

Abstract. The paper presents the test data on properties of rocks from Zhdanovskoe deposit located in the Pechenga area of the Murmansk Region. The nature of the elastic energy accumulation in rock specimens and their susceptibility to uncontrollable fracture in the dynamic mode are determined. The uniaxial and triaxial compression test data are used to find mechanical properties and energy characteristics of rock specimens. The tested rocks are assessed as hard and susceptible to dynamic fracture, which is one of the criteria of rockburst hazard.

1. Introduction
Zhdanovskoe copper–nickel deposit is located in the north-west of the Kola Peninsula, in the Pechenga area, and holds one of the largest copper–nickel reserves in Russia [1–3]. Currently, the deposit is operated by Severny Mine of Kola Mining and Metallurgical Company.

The deposit is composed of a few sheet-like ore bodies with bulges and twitches. The average thickness of the ore bodies is 23 m, and the average dip is 40°. Ore and enclosing rocks contain disjunctive discontinuities and intermediate faulting zones, though the rock mass is quite sustainable to the effect of mining. Until recently, Zhdanovskoe copper–nickel reserves were extracted by the open pit mining method. Actually, the transition from the open pit to underground mining has been implemented [4, 5].

The research carried out by the Mining Institute in Zhdanovskoe deposit is aimed at the rockburst hazard assessment [6]. To this end, it is required to determine properties of rocks in uniaxial and triaxial compression, brittle fracturability of rocks with high energy liberation, i.e. their dynamic fracturability, as well as to assess actual stresses in rock mass. The rockburst hazard rating of the deposit should be based on the analysis of these data [7].

2. Methods of the research
For the comprehensive lab-scale studies of Zhdanovskoe deposit rocks, hand specimens of four lithological varieties were taken from Central ore body (COB): tufaceous sediment, diabase, solid copper–nickel ore and serpentinous peridotite, as well as hand specimens of four lithological varieties were taken from South-West ore body (SWOB): tufaceous sediment, gabbro, solid copper–nickel ore and serpentinous peridotite. From the hand specimens 150×150×150 mm in size, cylindrical and cubic specimens were made. The cylinders had a height-to-diameter ratio of 2:1 (90×45 mm). The cubes had a side of 45 mm in size. The set of specimens for each kind of tests was not less 6 specimens.
Mechanical properties of the specimens were tested using MTS 816 RockTestSystem. The ultimate strengths in compression and tension, as well as the elasticity moduli and Poisson’s ratios were determined in uniaxial compression tests. The strength variation in the specimens was determined in triaxial compression tests with an increase in lateral pressure from 10 to 30 MPa. The triaxial compression testing procedure is described in [8].

Using the obtained values of a brittleness factor $K_b$ and a critical elastic strain energy ratios $W_c$ and $W_{3c}$ of rocks in uniaxial and triaxial compression, respectively, were calculated from the formulas below:

$$K_b = \frac{\sigma_t}{\sigma_c},$$

$$W_c = \frac{\sigma_t^2}{2E},$$

$$W_{3c} = \frac{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\nu(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)}{2E},$$

where $\sigma_s$ is the ultimate strength in uniaxial compression, MPa; $\sigma_t$ is the ultimate strength in uniaxial tension, MPa; $\sigma_1, \sigma_2, \sigma_3$ are the maximal, intermediate and minimal principal stresses, respectively, MPa; $E$ is the elasticity modulus, MPa; $\nu$ is Poisson’s ratio.

The resultant mechanical properties and energy characteristics of rocks from Zhdanovskoe COB and SWOB are compiled in Table 1. Regarding COB rocks, the highest compression strength and elasticity modulus belong to solid copper–nickel ore; tufaceous sediment and serpentinous peridotite are weaker and less elastic; diabase has the lowest values of the listed parameters. The tests revealed an inverse tendency: the lowest values for solid ore and tufaceous sediment, and the highest values for peridotite and diabase. The perfectly brittle rocks have $K_b = 0$ [9], which allows concluding that ore and tufaceous sediment are more brittle, while peridotite and diabase are less brittle.

Table 1. Mechanical properties and critical elastic strain energy of rocks from Central and South-West ore bodies of Zhdanovskoe deposit

| Rocks               | Density, g/cm$^3$ | $\sigma_{uc}$, MPa | $\sigma_t$, MPa | $E$, 10$^4$, MPa | $\nu$ | $K_b$ | Critical elastic strain energy, MJ/m$^3$ |
|---------------------|-------------------|--------------------|-----------------|------------------|-------|-------|--------------------------------------|
| COB tufaceous sediment | 2.80              | 140                | 12.7            | 8.29             | 0.24  | 0.09  | 0.12                                 |
| COB diabase         | 2.85              | 75                 | 15.3            | 6.66             | 0.27  | 0.20  | 0.04                                 |
| COB solid ore       | 2.92              | 185                | 12.8            | 8.42             | 0.26  | 0.07  | 0.20                                 |
| COB peridotite      | 2.95              | 95                 | 14.0            | 8.28             | 0.28  | 0.15  | 0.05                                 |
| SWOB tufaceous sediment | 2.78              | 85                 | 13.8            | 8.46             | 0.25  | 0.16  | 0.04                                 |
| SWOB diabase        | 3.01              | 100                | 18.0            | 6.47             | 0.28  | 0.18  | 0.08                                 |
| SWOB solid ore      | 4.55              | 160                | 12.6            | 8.48             | 0.26  | 0.08  | 0.15                                 |
| SWOB peridotite     | 2.85              | 165                | 16.4            | 8.52             | 0.25  | 0.10  | 0.16                                 |

The found values of the critical elastic strain energy are the energy which is accumulated as the specimens reach the ultimate strength and releases in fracture of the specimens. In this case, the higher accumulated energy means more intense (dynamic) fracture. Such fracture events in rock mass are analogous to different phenomena caused by confining pressure, from slabbing and spalling to rockbursts and induced earthquakes.
As regard COB rocks, the highest critical elastic strain energy in uniaxial compression belongs to solid ore. According to [10], the higher excess of the critical elastic strain energy over the threshold of 0.1 MJ/m³ means higher susceptibility of rocks to dynamic fracture. Consequently, the test solid ore should fracture in a pronounced dynamic mode, which is proved by the research findings. The fracture mode of the tufaceous sediment and peridotite specimens is less dynamic. For some specimens of diabase, the fracture behavior is similar to the conventional static mode, as flat spotting without dispersion of fragments. These rocks have the minimal value of the critical elastic strain energy. Regarding SWOB rocks, solid copper–nickel ore and serpentinous peridotite have the highest values of compression strength and elasticity modulus, while gabbro and tufaceous sediment are weaker and less elastic.

From the comparison of the brittleness factors of SWOB rocks, solid ore and peridotite feature the highest brittleness, while gabbro and tufaceous sediment are less brittle. Regarding the critical elastic strain energy, solid ore and peridotite are more susceptible to dynamic fracture, while the other two lithological varieties are less fracturable in the dynamic mode. For some specimen of tufaceous sediment, the fracture behavior was similar to the static mode.

From the comparison of the testing data of COB and SWOB rocks, solid copper–nickel ore is the most brittle and susceptible to dynamic fracture, while COB diabase and SWOB tufaceous sediment are the least brittle and dynamically fracturable. All other lithological varieties have intermediate values of these characteristics.

Using the triaxial compression test data of COB and SWOB specimens, their strength and energy characteristics are determined (Table 2). The highest increase in the strength with an increasing side pressure was observed in solid copper–nickel ore. The strength of COB diabase jumped in triaxial compression while the stronger tufaceous sediment specimen from COB exhibited no such effect. The much weaker specimen of SWOB tufaceous sediment showed a fast increase in the triaxial compression strength.

### Table 2. Strength and energy characteristics of rock specimens from Central and South-West ore bodies in triaxial compression

| Rocks                  | Triaxial compression strength, MPa | Critical elastic strain energy, MJ/m³ |
|------------------------|-----------------------------------|--------------------------------------|
|                        | $\sigma_2 = \sigma_3 = 10$   | $\sigma_2 = \sigma_3 = 20$ | $\sigma_2 = \sigma_3 = 30$ | $\sigma_2 = \sigma_3 = 10$ | $\sigma_2 = \sigma_3 = 20$ | $\sigma_2 = \sigma_3 = 30$ |
| COB tufaceous sediment | 155                          | 216                      | 242                      | 0.14                      | 0.26                      | 0.32                      |
| COB diabase            | 233                          | 264                      | 330                      | 0.39                      | 0.49                      | 0.75                      |
| COB solid ore          | 277                          | 351                      | 468                      | 0.44                      | 0.69                      | 1.22                      |
| COB peridotite         | 298                          | 329                      | 423                      | 0.52                      | 0.61                      | 1.00                      |
| SWOB tufaceous sediment| 271                          | 377                      | 442                      | 0.42                      | 0.80                      | 1.08                      |
| SWOB diabase           | 301                          | 380                      | 388                      | 0.68                      | 1.05                      | 1.07                      |
| SWOB solid ore         | 351                          | 398                      | 513                      | 0.71                      | 0.89                      | 1.47                      |
| SWOB peridotite        | 204                          | 228                      | 286                      | 0.23                      | 0.28                      | 0.44                      |

As follows from the behavior of the critical elastic strain energy of COB and SWOB rocks in triaxial compression in the figure, the highest elastic energy is accumulated in the solid ore specimens. When in fracture, this solid ore can release the highest energy in enclosing rock mass, which can provoke various dynamic phenomena. The lowest growth in the critical elastic strain energy is detected in the tufaceous sediment specimens from COB and in the serpentinous peridotite specimens.
from SWOB. These types of rocks fracture less dynamically in triaxial compression as compared with the other tested lithological varieties.

Change in critical elastic strain energy of rocks from (a) a Central ore body and (b) South-West ore body in triaxial compression:
1 — tufaceous sediment; 2 — diabase; 3 — solid copper–nickel ore; 4 — serpentinous peridotite; 5 — gabbro.

The comparison of the critical elastic strain energies of COB rocks in uniaxial and triaxial compression at the side pressure of 30 MPa show that in the latter case, the energy jumps by 3 times in tufaceous sediment, by 6 times in ore and by 18 times in diabase and peridotite. The largest increase in the critical elastic strain energy in triaxial compression is recorded in rocks which have lower strength and energy in uniaxial compression as compared with other specimens from COB. This may be connected with structural features of the specimens, such as sizes and cleavage of grains, density, etc. Regarding SWOB rocks in the triaxial compression tests, the energy jumped by 3 times in peridotite, by 10 times in copper–nickel ore, by 14 times in gabbro and by 25 times in tufaceous sediment. As with COB rocks, the highest increase in the energy in the triaxial compression tests is recorded in rocks which have lower strength and energy in uniaxial compression, namely, tufaceous sediment and gabbro; the minimal values are obtained in the peridotite specimens which have the highest strength and critical elastic strain energy in uniaxial compression.

3. Conclusions
In the course of the tests of rock specimens from Zhdanovskoe deposit, the mechanical properties and energy characteristics of these rocks have been determined. The analysis of the brittleness factors and critical elastic strain energies of the tested rock specimens shows that solid copper–nickel ore are the most brittle and the most susceptible to dynamic fracture; serpentinous peridotite from SWOB and tufaceous sediment from COB exhibit lower brittleness and dynamic fracturability; the least brittleness and nearly static fracture mode in uniaxial compression are the features of COB diabase and SWOB tufaceous sediment.

The traxial compression tests of the same rock specimens show that their strength and critical elastic strain energy change with an increasing side pressure differently owing to their structural features. For example, the rock specimens which area weaker and less susceptible to dynamic fracture when subjected to uniaxial compression (diabase and peridotite from COB, and tufaceous sediment and gabbro from SWOB) exhibit jump in the strength and energy characteristics in the triaxial compression tests, which means that these rocks are more susceptible to fracture in the dynamic mode. And vice versa, the stronger rock specimens more susceptible to dynamic fracture in uniaxial compression (tufaceous sediment from COB and serpentinuous peridotite from SWOB) exhibited lower increase in strength and critical elastic strain energy in triaxial compression. In connection with this, the rockburst hazard assessment of rocks requires determination of their mechanical properties and energy characteristics both in the conditions of uniaxial and triaxial compression.

The tested rock specimens from Zhdanovskoe deposit are assessed as brittle, susceptible to fracture in the dynamic mode and rockburst-hazardous.
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