Time variations in physicomechanical and acoustic properties of granite irradiated by accelerated electrons

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Abstract. In earlier R&D works executed at IM SB RAS the optimal dose of the granite treatment with accelerated electrons was experimentally established. It equals 10 kGy, this dose causes weakening of granite strength under uniaxial compression from 68.33 to 35.08 MPa, deformation modulus reduces from 13.19 to 7.04 GPa. This pretreatment permits to lower the compressive energy of granite core disintegration from 7.68 to 3.06 J and the crushing energy from 700.42 to 470.88 J. Of specific technological importance is dynamics of chronological variations in mineral properties after pretreatment of minerals with accelerated electrons. The present research aim is to study chronological variations in properties of granite, conventionally associated with deposits of such valuable elements, as Au, Sn, W, Mo, Li, Be, Rb, Bi, etc. The complex experiments on granite revealed that after a granite specimen is subjected to the high-energy electron irradiation, the increase in an absorbed dose causes first reduction in P- and S-waves velocities, then P- and S-wave velocities are growing and later again slowing down. The established experimental regularities of variations in granite properties relate to granite imperfections, specified by memory of the study rock. The most substantial variations in P- and S-waves velocities in the pretreated granite-core specimens within time interval up to 5360 hours after the irradiation are recorded for the adsorbed dose equal to 10 kGy. The established increase in P- and S-waves velocities versus a time interval after granite-core treatment with the adsorbed dose of more than 10 kGy could indicate a reduction in number of available imperfections and a probable strengthening of the study mineral material. Scientific novelty of the present research concerns the determination of chronological variations in granite properties and the beneficial feasibility to use the mineral weakening effect of in mineral processing operations.

1. Introduction
At present the mineral resources in our country are mainly developed thanks to intensive involvement of rebellious ore deposits and mining waste into commercial production. This tendency reveals both appreciable loss of commercially valuable components at mining and processing circuits as well as high operating and capital costs of marketable product production.

In recent years the manifold sophistication of mineral processing techniques is governed by the transition to process rebellious, finely disseminated and mostly poor mineral ore reserves where the valuable target minerals are overground and lost in slime products. Up to 40 % of valuable mineral loss at primary crude processing circuits fall on intergrowths content and up to 35 % of valuable loss are due to the content of fine fractions of less than 10 µm [1]. The ore pretreatment processes are designed to approach the feed size to size of mineral crystals in ores of perspective or commercial...
non-ferrous metals, tin, rare and rare-earth elements deposits. It is important to preserve the crystalline structure of valuable components. The ore pretreatment circuits involve machinery for fine (less than 20 µm) and superfine (less than 7 µm) grinding [2] with energy consumption up to 50 kW·h/t and higher.

In [3, 4] it is pointed out that processing properties of minerals depend on their structure and genesis which specify a certain degree of contrast in mineral properties in intergrown aggregates and feasibility of their modification by employing different effects. The technological mineralogy can provide exhaustive information on mineral composition, parameters of mineral structure for a mineral feed to be processed. Mineral and granulometric compositions indicate an optimal size of mineral feed disintegration required and a feasibility to liberate minerals in mineral processing operations.

In this connection it is worth noting the statement of Russian prominent scientist Corresponding Member of the USSR Academy of Sciences Plaksin I.N. that one of the flagship directions of mineral processing is the search for energy effects, capable to provide maximally complete and comprehensive utilization of mineral resources [5]. He was one of pioneers to substantiate the efficiency of external energy effects applied in mineral processing. Nowadays this direction in mineral processing is supported by Plaksin’s successors and followers [6–8].

The R&D reports of a number of Russian research institutes, including IM SB RAS, [9–11], state the feasibility to improve liberation of mineral aggregates and processing characteristics of rebellious mineral materials by introducing a feed pretreatment by an accelerated electron beam with the purpose to weaken mineral and rock strength. According to assay of mineral specimens from different deposits the mineral materials are as a rule polyminal and most of their composition is rocks, namely limestone, hornblende, and granite.

In [12] the optimal experimental dose established for granite irradiation by accelerated electrons is 10 kGy. It causes reduction in strength under uniaxial compression from 68.33 down to 35.08 MPa, and deformation modulus from 13.19 down to 7.04 GPa. This treatment enables to lower the compression energy of granite core disintegration from 7.68 down to 3.06 J and the crushing energy from 700.42 down to 470.88 J. Important for technological applicability is dynamics of variations in mineral component properties versus time after their accelerated electron irradiation. The present research work is intended to study time variations in granite properties associated with content of such valuable elements as Au, Sn, W, Mo, Li, Be, Rb, Bi, etc. in mineral deposits.

2. Experimental procedures and materials

The physicomechanical properties of granite were determined on cores of a regular cylindrical shape in terms of acting standards and procedures for equipment passed metrological examination and certification. Specimens were about 30 mm in diameter (d), 60 mm in height (h); height (h) to diameter ratio (shape factor h/d) for the test specimens was 2 within GOST 21153.2-84. The evaluation of rock strain properties were in compliance with the requirements [13-15].

Pretreatment of ready-made core specimens was realized by an accelerated electron beam by preset doses and energy of electrons equal to 2.4 MeV at ILU-6 commercial accelerator at the Budker Institute of Nuclear Physics, SB RAS.

Measurements of velocities of elastic P- and S-waves in granite cores were performed under procedure, described in GOST 21153.7-75 [15]. The schematic of the test stand for measurements of p- and s-wave velocities under atmosphere conditions is shown in Figure 1. The stand equipment consists of bottom 1 and top 2 bases; case 3, a core specimen 4 is placed between supporting faces into interior space. The case consists of bottom 5 and top 6 guides, interconnected by supporting columns 7 and screws 8. Spring-mounted sensors 9 and 10 are located in the interior space of the base. The sensors are connected to a pulse-generating block and signal-input block through circuit lines 11 and 12, respectively.
To determine velocities of P- and S-wave propagation a test core specimen is placed between supporting surfaces of bottom and top bases where sensors are pressed with springs to end faces of the test core specimens. The structure of the case provides coincidence of sensors axes. Length of the core specimen $L$ is measured with error within 0.1 mm.

Figure 2 demonstrates signal types. Oscillograms of signals are recorded through end-to-end scanning of the core specimen of 30 mm in diameter and 60 mm in length by a pair of identical sensors. Oscillograms are presented for a sensor with longitudinal oscillations in Figure 2a and for a sensor with transverse oscillations in Figure 2b. The working ultrasonic-range frequency of 200 kHz is used in core investigation. Calculations of P- and S-wave propagation velocities $V_P$ and $V_S$, respectively, in the test granite specimens, granite elasticity modulus and Poisson ratio were performed by formulas reported in [11, 13-15].

3. Experimental results
Basic experimental results on investigation into the effect of the accelerated electron pretreatment of granite cores on their mechanical and acoustic properties including different time intervals after the accelerated electron treatment are summarized in Tables 1 and 2.
### Table 1. Mechanical and dynamic test results for granite cores irradiated by high-energy accelerated electron beam.

| Specimen no. | Specimen characteristics | Velocity, m/s | Elasticity modulus, GPa | Poisson ratio |
|--------------|--------------------------|---------------|-------------------------|--------------|
|              | Length, mm | Diameter, mm | Weight, g | Density, kg/m³ | Longitudinal | Transverse |              |              |              |
| 1-14         | 59.45 | 29.54 | 103.64 | 2545.79 | 3989.79 | 2376.29 | 35.28 | 0.2242 |
|              | Cores with no accelerated electron treatment | | | | | | | |
| 3            | 60.7  | 29.4  | 104.0  | 2525  | 4223  | 2549  | 39.81 | 0.2135 |
| 4            | 59.9  | 29.5  | 104.0  | 2542  | 3892  | 2320  | 33.49 | 0.2245 |
| 5            | 56.9  | 29.6  | 97.0   | 2479  | 3543  | 2142  | 27.56 | 0.2121 |
| average      | 59.17 | 29.5  | 101.7  | 2515.3| 3886  | 2337  | 33.62 | 0.2167 |
| 6            | 59.5  | 29.5  | 102.0  | 2509  | 4114  | 2473  | 37.35 | 0.2172 |
| 7            | 57.0  | 29.5  | 97.0   | 2491  | 4112  | 2463  | 36.88 | 0.2202 |
| 8            | 60.0  | 29.6  | 104.0  | 2520  | 4054  | 2376  | 35.24 | 0.2382 |
| average      | 58.83 | 29.53 | 101.0  | 2506.7| 4093.3| 2437.3| 36.49 | 0.2252 |
| Cores irradiated by accelerated electrons at absorbed dose of 10 kGy | | | | | | | |
| 9            | 60.5  | 29.6  | 104.0  | 2499  | 3905  | 2339  | 33.38 | 0.2202 |
| 10           | 60.7  | 29.6  | 105.0  | 2515  | 3986  | 2479  | 36.61 | 0.1848 |
| 11           | 58.8  | 29.5  | 101.0  | 2514  | 4055  | 2430  | 36.23 | 0.2198 |
| average      | 60.0  | 29.57 | 103.3  | 2509.3| 3982  | 2416  | 35.41 | 0.2082 |
| Cores irradiated by accelerated electrons at absorbed dose of 15 kGy | | | | | | | |
| 12           | 58.5  | 29.5  | 100.0  | 2502  | 4082  | 2435  | 36.31 | 0.2239 |
| 13           | 59.0  | 29.5  | 100.0  | 2481  | 3858  | 2309  | 32.29 | 0.2210 |
| 14           | 60.0  | 29.6  | 103.0  | 2496  | 3886  | 2222  | 30.99 | 0.2571 |
| average      | 59.17 | 29.53 | 101.0  | 2493  | 3942  | 2322  | 33.20 | 0.2340 |
| Cores irradiated by accelerated electrons at absorbed dose of 20 kGy | | | | | | | |
| 15           | 60.6  | 29.7  | 104.0  | 2502  | 4082  | 2435  | 36.31 | 0.2239 |
| 16           | 59.7  | 29.5  | 100.0  | 2481  | 3858  | 2309  | 32.29 | 0.2210 |
| 17           | 60.0  | 29.6  | 103.0  | 2496  | 3886  | 2222  | 30.99 | 0.2571 |
| average      | 59.17 | 29.53 | 101.0  | 2493  | 3942  | 2322  | 33.20 | 0.2340 |

### Table 2. Determination of properties of granite core specimens irradiated by accelerated electron beams in different time intervals.

| Specimen no. | Absorbed dose, kGy | Specimen size, d-l, mm | Atmosphere conditions | Wave velocity, m/s | Elasticity modulus, GPa | Poisson ratio |
|--------------|---------------------|------------------------|----------------------|-------------------|------------------------|--------------|
|              |                     |                        |                      | longitudinal      | transverse             |              |
| 1-14         | 0                   | 29.5±59.45             | 3989.79              | 2376.29           | 35.28                  | 0.2242       |
| 3-5          | 5                   | 29.5±59.17             | 3886                 | 2337              | 33.62                  | 0.2167       |
| 6-8          | 10                  | 29.5±58.83             | 4093.3               | 2437.3            | 36.49                  | 0.2252       |
| 9-11         | 15                  | 29.5±60.0              | 3982                 | 2416              | 35.41                  | 0.2082       |
| 12-14        | 20                  | 29.5±59.7              | 3942                 | 2322              | 33.20                  | 0.2340       |

Measurements made directly after treatment

Measurements made in 200 hours after treatment

Measurements made in 1856 hours after treatment

Measurements made in 5360 hours after treatment
4. Discussion
It follows from Table 1 that average velocities of P- and S-wave propagation (V_P and V_S, respectively) in initial granite cores amounted to 3989.79 and 2376.29 m/s. These data do not contradict the evidence reported in [15]. This Table contains test data on granite cores after their irradiation by accelerated electrons. As the adsorbed dose is increased up to 20 kGy, velocities of longitudinal and transverse waves first diminish, then grow and again decline. In the case with core specimens treated at absorbed dose of 5 kGy the average velocities of P- and S-wave propagation equal 3886 and 2337 m/s; at dose of 10 kGy they are equal to 4093.3 and 2437.3 m/s. Experimental results cited in Table 1, also indicate that the irradiation of granite cores by the high-energy accelerated electron beam alters their elasticity modulus and Poisson ratio.

Variations in granite characteristics after irradiation relate to such fundamental property of rocks as memory and its diverse manifestations governed by available rock imperfections [16]. Complexity and variety of defects characterizing a complex pattern of rock failure are pointed out by a number of research scientists in [16, 17]. Imperfections of rocks can be considered in terms of several scale levels. Imperfections of the lowest level present spot defects of crystalline lattice: vacancies and interstitial atoms. Higher level of defects in grains is linear defects and dislocations. The grain structure of a rock can cause defects at grain interface boundaries specified by both mutual orientation of axes and physical properties. When investigating rock cores and small sections of a rock mass a higher level of defects related to micro- and macro fractures is considered. Defects of all the mentioned levels make contributions to memory construction.

It follows from Table 2 that velocities of longitudinal and transverse waves in untreated granite cores do not alter notably with time. The greatest variations in magnitudes of P- and S- wave velocities in granite cores treated by accelerated electrons with time are observed when the adsorbed dose amounts to 10 kGy. Thus, given that immediately after the treatment their magnitudes are 4093.3 and 2437.3 m/s; 200, 1856 and 5360 hours later P-wave velocity values are 4152, 4248, and 4331,7 m/s; and S -wave velocity values are 2463, 2514 and 2519.3 m/s. According to Table 2 the elasticity modulus for granite cores accepts maximum values at the absorbed dose magnitude equal to 10 kGy disregarding time factor.

5. Conclusions
The established fact of increase in the longitudinal and transverse waves velocities versus a time interval since treatment of granite cores make the grounds to suppose that number of defects and probability of the mineral material strengthening used to lower. Experimentally proved time-dependent peculiarities in granite behavior after it is treated by accelerated electrons should be considered in ore pretreatment and processing of rebellious finely-disseminated mineral materials. It is proposed to take into account the experimentally proved time-dependent peculiarities in granite behavior after it is irradiated by accelerated electrons in ore pretreatment and processing of rebellious finely-disseminated mineral materials.

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