Acta Geodyn. Geomater.Vol.1, No.4 (136), 85-91, 2004

A COMPARISON OF PHYSICAL AND MECHANICAL CHARACTERISTICS OF KOLA SUPERDEEP BOREHOLE CORE SAMPLES AND THEIR SURFACE ANALOGUES

Felix F. GORBATSEVICH 1), **Vadim L. IL'CHENKO** 1), **Jiřina TRČKOVÁ** 2)*,
Roman ŽIVOR 2) **and Yury P. SMIRNOV** 3)

1) *Geological Institute of the Kola Science Centre of RAS, Apatity, Russia*
2) *Institute of Rock Structure and Mechanics AS CR, Prague, Czech Republic*
3) *SIC "Kola Superdeep", Zapolyarny, Russia*
**Corresponding author's e-mail*: trckova@irsm.cas.cz

(*Received* September 2004, *accepted* December 2004)

ABSTRACT

The article presents experimentally determined physical and mechanical properties and elastic anisotropy of three core samples of metamorphic rocks (gneisses), which were drilled out and lifted from depths of 6849 – 8411 m of the Kola Superdeep Borehole (SD-3) and their surface analogues. Acoustopolariscopic measurements of parameters of anisotropy of samples were carried out in the Geological Institute of the Kola Science Centre of RAS, Apatity. Particle density, bulk density, porosity, simple compressive strength, modulus of deformation, Young´s modulus of elasticity and Poisson´s ratio were determined in the Institute of Rock Structure and Mechanics of AS CR, Prague. Laboratory tests known from rock mechanics were used for this purpose. From the results obtained, differences in physical properties between samples from SD-3 and the surface are evident.

KEYWORDS: Kola Superdeep Borehole, laboratory tests, physical and mechanical properties

1. INTRODUCTION

In the context of complete investigations at the Kola Superdeep Borehole, physical and mechanical properties and anisotropy of different rocks from various depths of this borehole and their surface analogues have been studied by several methods. Previous investigations of a core of the Kola Superdeep Borehole (SD-3) found essential variations of anisotropy of elastic properties of rocks in SD-3 (Gorbatsevich, 1995; Orlov and Lobanov, 1998.). The maximum anisotropy was marked in the parts which correspond to fault zones. For example, a fault with intrusion of ultramafic dykes and copper-nickel mineralization occurred in the vicinity of depths of 1.7-1.9 km (Gorbatsevich et al., 2000), at the depth of 4.3 km a plane of the Luchlompolo fault was found (Ilchenko et al., 2004) and at the depth of 6.84 km a tectonic boundary between rock complexes of Archaean and Proterozoic age is located (Kozlovsky, 1987). The value of elastic anisotropy parameter is directly related to changes of cross section of the borehole, namely with occurrence of flaking of its walls i.e. cavernosity (Orlov and Lobanov, 1998).

The basic physical properties – particle density, bulk density and porosity, and the mechanical and deformational properties - simple compressive strength, modulus of deformation, Young´s modulus of elasticity and Poisson´s ratio for chosen rocks from the borehole were previously determined and their changes with depth of occurrence in the borehole were studied (Trčková et al., 2002). Obtained particle density and bulk density were nearly similar for all tested samples. The porosity increased slowly with depth. Marked differences in strength properties were found between samples from the Archaean Complex (lower part of the borehole) and samples of the same rocks from the Proterozoic Complex (upper part of the borehole). The simple compressive strength of the samples from the lower part of the borehole was significantly lower than of the rocks from the upper part. The values of the deformation modulus, Young's modulus and Poisson's ratio obtained from samples of the Proterozoic Complex were considerably higher than those from the Archaean Complex.

A study of elastic anisotropy and other physical and mechanical properties of rocks was carried out on the borehole SD-3 core samples which were drilled out and lifted from depth. Tectono-caissonic effect is partly in decompacted condition, which affects the physical properties (Gorbatsevich, 2003). The nature of the decompaction reflects a stress in a point of the core sampling. The main microfractures occur in the direction of the greatest pressure, which was applied in a rock mass (Kern et al., 2001). The character of elastic anisotropy of a sample can reflect parameters of the actual stress field only in the case if elastic properties of this sample were close to isotropic at the point of sampling.

Table 1 Tested samples from SD-3 and their surface analogue samples

SD-3 deep samples			Corresponding surface samples	
Sample No	Depth (m)	Rock	Sample No	Rock
22515	6849	gneiss	1-02	amphibole-biotite-plagioclase gneiss
26609	7913	amphibole-epidote-biotite-plagioklase gneiss	2-02	biotite-plagioclase gneiss
28937	8411	biotite-plagio-gneisso-granite (migmatite)	4-02	biotite-plagioclase gneiss

To a certain extent the correctness of such an approach can be established by comparing with properties of specimens of the SD-3 core with their analogues collected from the surface. For this purpose, determination of elastic, physical, mechanical and anisotropic properties of these samples was conducted.

2. BOREHOLE CORE SAMPLES AND THEIR SURFACE ANALOGUES

To realize the experiments three samples of the SD-3 core from the top of the Archaean part of the section (6849-8411 m) were collected. This part of the borehole is distinguished with the greatest intensity of flaking of its walls (Kozlovsky, 1987). For comparison, three surface analogues, similar in petrographic and textural-structural characteristics to the appropriate samples of the SD-3 core, were collected from rocks of the Archaean frame of the Pechenga structure. Petrographic and textural-structural characteristics of the samples correspond to the group of biotite-plagioclase gneisses (Table 1).

Specimens of dimension 25 x 25 x 50 mm cut from the SD-3 core and rock analogue samples of similar dimensions were tested. Sides of the cuboids were labelled with marks *X, Y, Z (1, 2, 3)*. Side *Z* was normal to the axis of the core, while direction *X* and *Y* were chosen arbitrary. These specimens were consecutively over-drilled as cylinders 25 mm in diameter and 50 mm high and used for strength and deformational tests. The remainder after drilling specimen and specimens after given tests were used to determine physical properties of the tested rocks.

3. MEASUREMENT TECHNIQUES

3.1. *ANISOTROPY*

At the first stage of investigations acoustopolariscopic measurements of parameters of anisotropy of samples were carried out in the Geological Institute of the Kola Science Centre of RAS, Apatity, (Gorbatsevich, 1995). The principle of the method of acoustopolarization measurements (acoustopolariscopy) is the same as the polariscopy method in optics. An acoustopolariscope apparatus was used for these measurements. Apparatus consists of a transducer, radiating purely transverse, linear polarized shear waves and transducer of the same type for receiving the waves. Before the first stage of measurements the polarization planes (PV) of transducers are brought in line (VP-position). The sample prepared for measurements is placed between the transducers. In a sequence of measurements the sample is rotated through 360^0. The signal amplitudes, transmitted through the sample, are measured on the screen of a recording device. The second stage of measurements is conducted with polarization planes of the source and receiver intersecting at 90^0 (VC-position). Again, the measurements are conducted through a 360^0 rotation of the sample. These measurements produced acoustopolarigrams of anisotropic samples for parallel (VP) and intersecting (VC) directions of transducers polarization planes.

Measurements were carried out for all three pairs of sample sides on a working frequency of 1,2 MHz. At presence of elastic anisotropy in a sample these diagrams have, as a rule, a view of 4-petal figure (Fig. 1). Orientation of projections of elements (axes, planes) of elastic symmetry can be found by drawing straight lines through opposite minima of acoustopolarigrams VC.

Acoustopolarigrams (Fig. 1) were obtained both for deep samples, and for the samples collected from the surface. Orientation of projections of elements of elastic symmetry for three sides of each sample was determined. Then, according to the revealed directions, velocities of longitudinal *(V_p)* and transversal *(V_s)* oscillations were determined and quasi-matrixes of velocities V_{ij} were made (Gorbatsevich, 1995):

$$V_{ij} = \begin{vmatrix} V_{11} & V_{12} & V_{13} \\ V_{21} & V_{22} & V_{23} \\ V_{31} & V_{32} & V_{33} \end{vmatrix}, \qquad (1)$$

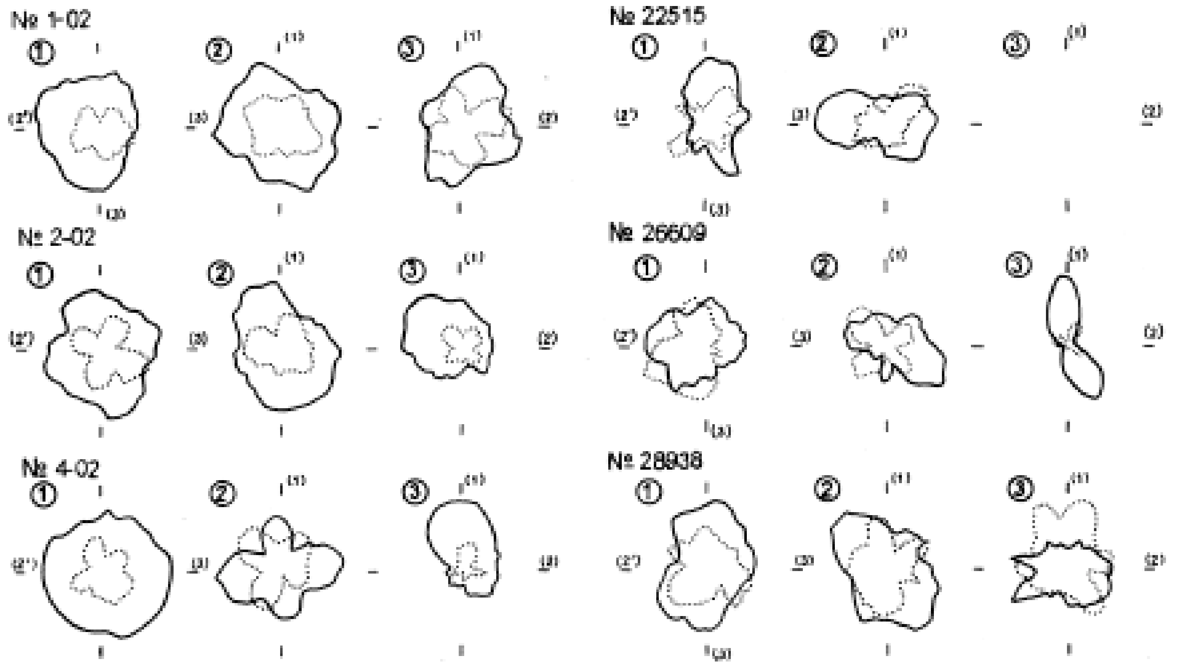

Fig. 1 Acoustopolarigrams (VP - solid line, VC - dotted line) of the samples made of the SD-3 core (the right part of the figure) and their analogues from the surface (the left part of the figure).

The following order of indexing measured values is presented in quasi-matrix. V_{11} is the compression wave propagation velocity, measured in the direction 1-1'; V_{22} is the same in the direction 2-2'; V_{33} is the same in the direction 3-3'; V_{12} is the shear wave propagation velocity, measured in the direction 1-1' with PV orientation in the direction 2-2'; V_{13} is the same in the direction 1-1' with PV orientation in the direction 3-3'; V_{21} is the same in the direction 2-2' with VP orientation in the direction 1-1'. Similarly V_{23}, V_{31}, V_{32} are marked.

Values of elastic anisotropy for transversal waves B is determined using the data of quasi-matrix and the following formulas (Gorbatsevich et al., 2000):

$$B = \sqrt{B_1^2 + B_2^2 + B_3^2} \cdot 100\,(\%), \qquad (2)$$

where $B_1 = \dfrac{2(V_{12} - V_{13})}{V_{12} + V_{13}}$, $B_2 = \dfrac{2(V_{21} - V_{23})}{V_{21} + V_{23}}$,

$$B_3 = \frac{2(V_{31} - V_{32})}{V_{31} + V_{32}}$$

are parameters of birefringence on facets 1, 2 and 3.

Factors of anisotropy on longitudinal waves were calculated as some deviator of values of *Vii* in quasimatrix:

$$A_p = \frac{1}{V_{cp}} \sqrt{(V_{11} - V_{cp})^2 + (V_{22} - V_{cp})^2 + (V_{33} - V_{cp})^2} \cdot 100\,(\%) \qquad (3)$$

$V_{cp} = \mathbf{V_P} = (V_{11} + V_{22} + V_{33})/3$ is the average velocity of distribution of longitudinal waves in a sample.

Density ρ was determined by the method of Archimedes. Then under well-known formulas from the theory of elasticity elastic constants E, G, ν were calculated: $E=2G(1+\nu)$, $G=\rho V_s^2$, $\nu=(F-2)/(2F-2)$, where $F=V_p^2/V_s^2$. Moduli E, G, as well as Poisson´s ratio ν was calculated, using average spreading velocities of longitudinal $\mathbf{V_p}$ and transversal $\mathbf{V_s}$ oscillations from the data of quasimatrix V_{ij}. Results of determinations are shown on Fig. 1 and in Table 2 and Table 3.

3.2. PHYSICAL, MECHANICAL AND DEFORMATIONAL PROPERTIES

Particle density, bulk density, porosity, simple compressive strength, modulus of deformation, Young´s modulus of elasticity and Poisson´s ratio were determined in the Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic. The laboratory tests known from rock mechanics were used for this purpose.

Table 2 Elastic characteristics of SD-3 core samples

Sample No	Quasimatrix V_{ij} (km/s)	Velocity ongitudinal waves **V_p** (km/s) transverse waves **V_s** (km/s)	Modulus of elasticity E (GPa) Shear modulus G (GPa) Poisson's ratio ν	Parameter of anisotropy longitudinal waves A_p (%) transverse waves B (%)
22515	3.80 2.70 2.73 2.60 4.13 1.60 - - -	3.96 2.41	37.7 15.6 0.21	- -
26609	3.92 2.07 2.18 1.53 2.14 2.16 1.98 1.74 2.64	2.90 1.94	22.2 10.2 0.09	44.6 34.6
28937	3.39 2.31 2.24 2.40 3.68 2.48 1.98 2.29 3.21	3.43 2.28	30.1 13.7 0.10	10.0 4.1

Table 3 Elastic characteristics of surface analogue samples

Sample No	Quasimatrix V_{ij} (km/s)	Velocity longitudinal waves **V_p** (km/s) transverse waves **V_s** (km/s)	Modulus of elasticity E (GPa) Shear modulus G (GPa) Poisson's ratio ν	Parameter of anisotropy longitudinal waves A_p (%) transverse waves B (%)
1-02	4.71 2.96 2.74 2.92 4.55 2.78 2.79 2.76 4.29	4.52 2.82	49.4 20.9 0.18	6.6 9.5
2-02	4.17 2.74 2.54 2.85 4.62 2.57 2.49 2.63 3.77	4.19 2.64	42.7 18.3 0.17	14.3 12.8
4-02	5.47 3.24 3.24 3.35 5.14 3.18 3.26 3.31 5.26	5.29 3.26	67.3 28.3 0.19	4.5 5.2

The particle density (mass per unit volume) was determined applying the pyknometer method. The bulk density was determined on irregular specimens coated with paraffin wax using the water displacement method. The total porosity, defined as the ratio of the volume all pores (open and closed) to the total volume of the rock specimen, was calculated from the bulk density of the dry specimen ρ_d and particle density ρ_S from the formula:

$$n = (1 - \frac{\rho_d}{\rho_S}) \cdot 100(\%) \qquad (4)$$

Compressive strength and axial and lateral deformations were measured at uniaxial compression. Since only one specimen from each other rock sample (core sample or surface analogue) was prepared, the standard progress of the laboratory tests could not be followed. To determine properties of the tested rocks, we could not use the standard methodology described in Suggested Methods of the International Society of Rock and Soil Mechanics (Brown, 1981) and European Standards (EN 1936), because three specimens are the minimal number for each of the tests.

Unconfined compressive strength, axial strain (ε_A) and lateral strain (ε_L) were measured in the uniaxial compression test. One cycle of loading and unloading was applied in the loading process during the compression test to calculate deformational properties. To obtain unconfined compressive strength, after this cycle, the samples were loaded until failure. Because the final strength value was not known, the cycle was assessed empirically and additionally it was calculated that it roughly corresponded to about 67% on average (core samples) and 72% on average (analogues) of the final strength value.

From the measured strains, the values of the deformation modulus *E* $_{def}$, Young's modulus *E* and Poisson's ratio ν, were determined by formulae known in rock mechanics.

Measurement results are presented in Tables 4-7.

Table 4 Moduli of elasticity and deformation, Poisson's ratio of SD-3 core samples

Samples No	Simple compressive strength σ_c (MPa)	Modulus of deformation E_{def} (GPa)	Modulus of elasticity E (GPa)	Poisson's ratio ν
22515	111.8	32.0	40.2	0.08
26609	99.4	26.0	36.0	0.34
28937	168.5	43.3	48.0	0.21

Table 5 Moduli of elasticity and deformation, Poisson's ratio of surface analogue samples

Samples No	Simple compressive strength σ_c (MPa)	Modulus of deformation E_{def} (GPa)	Modulus of elasticity E (GPa)	Poisson's ratio ν
1 - 02	158.2	56.3	65.0	0.24
2 - 02	146.0	61.5	68.4	0.33
4 - 02	213.5	89.0	114.5	0.33

Table 6 Bulk and particle density, porosity of SD-3 core samples.

Samples No	Bulk density ρ (g·cm^{-3})	Particle density ρ_s (g·cm^{-3})	Total porosity n (%)
22515	2.68	2.74	3.2
26609	2.71	2.76	2.1
28937	2.63	2.76	4.9

Table 7 Bulk and particle density, porosity of surface analogue samples

Samples No	Bulk density ρ (g·cm^{-3})	Particle density ρ_s (g·cm^{-3})	Total porosity n (%)
1 - 02	2.63	2.75	4.5
2 - 02	2.62	2.76	5.0
4 - 02	2.66	2.71	2.0

4. MEASUREMENT RESULTS

Results of acoustopolariscopy of the SD-3 samples and their analogues collected from the surface is shown in Figure 1. The diagrams of the surface analogue samples differ by smoothness of outlines and by greater isometricity, from acoustopolarigrams, obtained on the core samples from SD-3. All samples from the surface can be related to the transverse-isotropic type of elastic symmetry with insignificant display of Linear Acoustic Anisotropy of Absorption (LAAA) (Gorbatsevich, 1995).

Acoustopolarigram outlines, both VP and VC, of the core samples are distinguished by abrupt change of amplitude that testifies to their significant heterogeneity and influence of microfracturing. Sample 22515 is strongly decompacted in the *Z* direction, and it was not possible to execute measurement in this direction. Samples 22515 and 26609 display, besides anisotropy, significant LAAA. Sample 22515 shows LAAA of linear, and 26609 of planar type. Acoustopolarigram of sample 28938 specifies significant heterogeneity of the rock. In this connection it is possible to assume that the rock at the sampling point has experienced consecutive action of several stress fields with differently oriented components (Il'chenko et al., 1999). It is probable that differently oriented stresses occurred at different times.

The obtained results cannot be considered as characteristics either for the surface rocks, or for the rocks of the SD-3. However, the data obtained enable a comparative analysis of sample parameters, to reveal distinctive attributes. For example, acoustopolariscopy has shown that the presence of significant heterogeneity and a high degree of manifestation of effect of the linear acoustic anisotropy of absorption distinguish core samples of the SD-3 rocks. Both the surface and the core samples are elastic-anisotropic. However, by outlines of VC diagrams, the degree of elastic anisotropy of the core samples is higher. This follows from the comparison of factors and the anisotropy parameter (Tables 2 and 3). Factor A_P and parameter B of the core samples change within the limits of 10.0-44.6 % and 4.1-34.6 % respectively. For the surface samples variation of A_P is 6.6-14.3 %, and B 5.2-12.8 %.

The next distinctive feature is considerably smaller average propagation velocities of longitudinal **(V_p)** and transversal **(V_s)** oscillations in the core samples. Average propagation velocities of longitudinal waves in the samples from the surface are 1.14-1.54 times higher than in the core samples, for transversal wave velocities 1.17-1.42 times.

Comparison of dynamic moduli of elasticity E and of shear G shows an even greater excess of these values for the surface samples (Tables 2 and 3). Modulus E of the surface samples exceeds that of the core samples by 1.31-2.23 times. Modulus G of the surface analogues is 1.34-2.06 times higher than that of the core samples. The dynamic Poisson ratio of the surface samples is on average also higher ($\nu_{cp} = 0.18$) than that of the samples from SD-3 ($\nu_{cp} = 0.13$).

Similar correlations between parameters of the static moduli of deformation, elasticity and Poisson´s ratio are observed for the surface and the core samples (Tables 4 and 5). On average, moduli of deformation and elasticity of the core samples are 2 times lower than these of the surface samples. The average Poisson´s ratio of the surface samples is the same as of the core samples.

The unconfined compressive strength values of the core samples are on average about 27% less than their analogues, and range from 32 – 21%.

A certain difference, first of all in velocity, elastic and deformation properties between the rock samples collected from the surface and the samples taken from depths of 6849 - 8411 m is observed. The difference in average values of the bulk and particle density and porosity of the rocks from SD-3 and the surface rocks is insignificant. The effect of a decompacting mechanism on the rocks from SD-3 on extraction from the borehole represents the most logical conclusion (Gorbatsevich, 2003). During extraction of samples from great depths and their release from lithostatic pressure, many microfractures are formed at grain boundaries and inside grains. These microfractures extend by the propagation of ultrasonic oscillations. The mechanism of closure of microfracture edges during loading of samples leads to increased values of static moduli of elasticity and deformation.

The given investigation has revealed an interesting feature of the microfractures arising due to unloading of the deep samples. It follows from the data of Tables 6 and 7 that values of porosity of the core and the surface samples calculated by means of pyknometric method practically do not differ. It means that the microfractures arising as a result of decompaction are so thin and have such small volume, that they do not influence the porosity opened when crushing a sample into fine grains.

Note also tendencies of change of properties, common for the core samples, as well as for samples of surface analogues. For example, sample No. 26609 has the lowest average propagating velocities of longitudinal and transverse waves, moduli of elasticity and shear, modulus of deformation, as well as the sample analogue No. 2-02 corresponding to this sample. The above listed parameters of sample No. 28937 are higher than of the other SD-3 core samples. The surface analogue sample No. 4-02 appropriate to it also differs from the other analogue samples by the highest values of velocity and elastic characteristics. Both for the core and for the surface samples, the greatest elastic anisotropy is marked for those samples, which have shown the greatest values of velocity and deformation parameters.

Accordingly the determined values of the physical and mechanical properties have only an informative character. Their validity is related to the tested specimen and they cannot be considered as representative properties of the tested rocks. However, test results allow some conclusions to be made. Certain distinctions between analogue samples collected from the surface and the samples from SD-3 were observed.

5. CONCLUSIONS

Physical properties of rocks depend mainly on the type of rock and its modal composition and indicate whether both core sample from SD-3 and surface analogue are very close together. On the other hand, mechanical and deformational properties can be greatly affected by different power conditions in the borehole and on the surface and also by the drilling method and decompacting of the core samples during lifting the core from depth to the surface.

It follows from the results obtained that there is a certain difference in physical properties between the samples from SD-3 and the surface ones. Velocity, elastic and deformation characteristics of these groups of rock-samples differ in the main. Propagation velocities of longitudinal and transverse oscillations, parameters of elasticity and strengthening of core samples are 1.2-2 times lower than the surface samples. Core rocks show higher degree of anisotropy than the rocks collected from the surface. The difference in velocity and deformation characteristics of the core and the surface samples arises due to the formation of a mass of microfractures when releasing the SD-3 samples from lithostatic pressure. Thus, the degree of decompacting of the SD-3 samples, registered through velocity and elastic parameters, can serve as a measure of stress in the rock mass at the point of sampling.

ACKNOWLEDGEMENT

The work was carried out within the framework of international project INTAS-01-0314 and RFBR grant 03-05-64169.

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