Laboratory studies of geomechanical properties of deep-level rocks

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Abstract. The article describes the lab-scale tests of the deformation and strength characteristics of rocks extracted from great depths. Samples of high-grade ore, cupriferous ore, disseminated ore, hornfels and limestone were subjected to tension, uniaxial compression and triaxial compression, and the failure envelopes were plotted. The change in the value of cohesion determined from Mohr’s envelopes in tension and uniaxial compression as well as in tension and triaxial compression is analyzed. The values of relative changes in cohesion and in uniaxial and triaxial compression strengths obey strong correlation.

1. Introduction

The underground construction and mining industries operating at great depths permanently deal with problems of geomechanics. In order to avoid or minimize unnecessary expenditures in mineral mining it is required to have a reliable prediction of rock mass behavior. Deep-level rock mass experiences complex stress state, which should taken into account in geotechnologies. The actual level of deep-level stress can exceed the uniaxial compression strength determined in lab-scale tests. Accordingly, a failure envelope plotted using the data of uniaxial compression and tension tests can offer inadequate characteristic of strength of deep-level rocks. For this reason, it is necessary to study behavior of rocks in different stress states, in particular, under triaxial compression. Many published studies are available on mechanical properties of rocks under triaxial compression and failure envelope construction, for example, [1–9].

This study is aimed to characterize strength properties of five rock types: high-grade ore, cupriferous ore, disseminated ore, hornfels and limestone sampled at a depth of 1600 m, subjected to different loading (tension, uniaxial compression and triaxial compression) and to construct their failure envelopes.

2. Laboratory test results

Core samples were loaded on Instron 8802 sevo-hydraulic testing machine at a loading program set by displacement of grips at a rate of 0.1 mm/s. In the course of loading, the continuous records of the change in the length and diameter of a sample, axial load and, additionally under the triaxial compression, lateral pressure were filed. Preparation of samples, experimentation and determination of strength characteristics followed the procedures under the state standards GOST 28985–91, 21153.2–84, 21153.3–85, 21153.8–88 and 21153.7–75. The uniaxial and triaxial compression tests were carried out on cylindrical samples 60 mm in length with a diameter of 30 mm; tensions tests—samples 30 mm
long with a diameter of 30 mm. Using the 60/30 mm samples, the dynamic Young modulus and dynamic Poisson’s ratio were determined. The images of the core samples are shown in Figures 1a–1e.

![Core samples before testing: (a) high-grade ore; (b) cupriferous ore; (c) disseminated ore; (d) hornfel; (e) limestone.](image)

**Figure 1.** Core samples before testing: (a) high-grade ore; (b) cupriferous ore; (c) disseminated ore; (d) hornfel; (e) limestone.

The triaxial loading was carried out by the Karman scheme: simultaneous axial force and lateral pressure (hydrostatics) up to a certain value of the lateral pressure (5 MPa in these tests), then the axial force was increased until failure of the core samples. Deformation curves were plotted for each sample: axial stress–axial strain; axial stress–transverse strain. The strength characteristics of the core sample under uniaxial and triaxial compression, namely, limit strength, Young’s modulus and Poisson’s ratio, are compiled in Table 1 (averaged values).

**Table 1.** Strength test results for core samples: average values of limit strength \( \sigma_{\text{lim}} \), Young’s modulus \( E \) and Poisson’s ratio \( \nu \).

| No. | Rock type      | Test                      | Limit strength \( \sigma_{\text{lim}} \), MPa | Young’s modulus \( E \), GPa | Poisson’s ratio \( \nu \) |
|-----|----------------|---------------------------|---------------------------------------------|-----------------------------|--------------------------|
| 1   | High-grade ore | Uniaxial compression      | 95                                          | 12.406                      | 0.219                    |
|     |                | Triaxial compression 5 MPa| 160                                         | 18.264                      | 0.159                    |
|     |                | Tension                  | 8                                           | —                           | —                        |
|     |                | Uniaxial compression      | 150                                         | 9.684                       | 0.225                    |
|     |                | Triaxial compression 5 MPa| 230                                         | 15.944                      | 0.168                    |
|     |                | Tension                  | 23                                          | —                           | —                        |
| 2   | Cupriferous ore| Uniaxial compression      | 90                                          | 13.169                      | 0.208                    |
|     |                | Triaxial compression 5 MPa| 127                                         | 17.221                      | 0.196                    |
|     |                | Tension                  | 17                                          | —                           | —                        |
|     |                | Uniaxial compression      | 103                                         | 11.562                      | 0.205                    |
|     |                | Triaxial compression 5 MPa| 157                                         | 17.979                      | 0.173                    |
|     |                | Tension                  | 27                                          | —                           | —                        |
| 3   | Disseminated ore| Uniaxial compression      | 67                                          | 9.601                       | 0.219                    |
|     |                | Triaxial compression 5 MPa| 121                                         | 14.977                      | 0.175                    |
|     |                | Tension                  | 12                                          | —                           | —                        |
| 4   | Hornfel        | Uniaxial compression      | 56                                          | 12.080                      | 0.197                    |
|     |                | Triaxial compression 5 MPa| 157                                         | 17.221                      | 0.196                    |
|     |                | Tension                  | 27                                          | —                           | —                        |
| 5   | Limestone      | Uniaxial compression      | 67                                          | 9.601                       | 0.219                    |
|     |                | Triaxial compression 5 MPa| 121                                         | 14.977                      | 0.175                    |
|     |                | Tension                  | 12                                          | —                           | —                        |
Figure 2. Resultant failure curves for: (a), (b) high-grade ore; (c), (d) cupriferous ore; (e), (f) disseminated ore; (g), (h) hornfels; (i), (j) limestone under tension and triaxial compression (at 5 MPa) in (a), (c), (e), (g), (i), under tension and uniaxial compression in (b), (d), (e), (h), (j). Dashed line—tension; dash-and-dot line—uniaxial compression; dash-and-two dots—triaxial compression; solid line—Mohr’s envelope.
Failure curve is a Mohr’s envelope in the normal and shear stress coordinates. According to [5, 6], failure curves are constructed by: plotting circles of tension and uniaxial compression and adding them with 3 circles of triaxial compression at different levels of lateral pressure. However, as experiments show, it is sometimes impossible to draw an easy curve to envelope all 5 semicircles. Eventually, either data of uniaxial or triaxial compression are disregarded, or an average envelope is drawn, which inaccurately describes specific limiting state. Figures 2a–2j present the failure curves plotted for 5 types of rocks by two methods separately: Mohr’s envelopes under tension and uniaxial compression and Mohr’s envelopes under tension and triaxial compression (5 MPa).

The values of cohesion and internal friction angle are given in Table 2. For the tested types of rocks, the values of cohesion in two different methods differ by 11 to 18%; this difference in the values of internal friction angle is from 5 to 17%. Cohesion and internal friction angle determined in the tension and uniaxial compression tests are always lower than the values of these characteristics obtained in the tension and triaxial compression tests in one and the same type of rock. Unfortunately, due to deficiency of core materials, the authors had no opportunity to test the effect of different lateral pressures in the triaxial compression on the values of cohesion and internal friction angle.

**Table 2. Cohesion and internal friction angle determined in the tests of core samples.**

| No. | Rock type         | Cohesion $c$, MPa | Internal friction angle $\phi$, deg |
|-----|-------------------|-------------------|------------------------------------|
| 1   | High-grade ore    | 13.44*            | 58.0*                              |
|     |                   | 15.44**           | 60.75**                            |
| 2   | Cupriferous ore   | 31.11             | 48.9                               |
|     |                   | 35.55             | 54.4                               |
| 3   | Disseminated ore  | 20.28             | 43.8                               |
|     |                   | 22.58             | 48.1                               |
| 4   | Hornfel           | 28.46             | 37.3                               |
|     |                   | 32.43             | 43.6                               |
| 5   | Limestone         | 14.65             | 45.4                               |
|     |                   | 17.33             | 52.2                               |

*Upper value in tension and uniaxial compression; **Lower value in tension and triaxial compression

Table 3 and Figure 3 present the values of ratios of cohesions obtained in two methods and ratios of limit strengths of triaxial compression/tension; uniaxial compression/tension and triaxial compression/uniaxial compression.

The correlation factors for the values in column 2 and columns 3–5 in Table 3 are calculated from the formula:

$$r = \frac{n \sum_{i}^{n} x y - \left( \sum_{i}^{n} x \right) \left( \sum_{i}^{n} y \right)}{\sqrt{n \sum_{i}^{n} x^2 - \left( \sum_{i}^{n} x \right)^2} \sqrt{n \sum_{i}^{n} y^2 - \left( \sum_{i}^{n} y \right)^2}}$$

where $x$ stands for $(c^{**} - c^{*})/c^{*}$, $y$—for $\sigma_{\text{tens}}^{\text{lim}}/\sigma_{\text{tens}}^{\text{lim}}$, $\sigma_{\text{tens}}^{\text{lim}}/\sigma_{\text{tens}}^{\text{lim}}$, $\sigma_{\text{tens}}^{\text{lim}}/\sigma_{\text{tens}}^{\text{lim}}$. The calculated correlation factors are given in Table 3.
Table 3. Ratios of cohesions determined by two methods, as well as ratios of limit strengths in the tests of triaxial compression/tension, uniaxial compression/tension and triaxial compression/uniaxial compression.

| No | Rock             | \((c^{**} - c^*) / c^*\) | \(\sigma_{\text{tcom}}^{\text{lim}} / \sigma_{\text{tens}}^{\text{lim}}\) | \(\sigma_{\text{ucom}}^{\text{lim}} / \sigma_{\text{tens}}^{\text{lim}}\) | \(\sigma_{\text{tcom}}^{\text{lim}} / \sigma_{\text{ucom}}^{\text{lim}}\) |
|-----|------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 1   | High-grade ore   | 0.15                     | 0.95                     | 0.92                     | 0.41                     |
| 2   | Cupriferous ore  | 0.14                     | 0.90                     | 0.85                     | 0.35                     |
| 3   | Disseminated ore | 0.11                     | 0.87                     | 0.81                     | 0.29                     |
| 4   | Hornfel          | 0.14                     | 0.83                     | 0.74                     | 0.34                     |
| 5   | Limestone        | 0.18                     | 0.90                     | 0.82                     | 0.45                     |
|     | Correlation factor | 0.379                   | 0.165                   | 0.954                    |                           |

- \(c^*\)—cohesion from the results of tension and uniaxial compression tests;
- \(c^{**}\)—cohesion from the results of tension and triaxial compression tests.

Figure 3. Relationship between ratios of strength characteristics (axis of ordinates) for different types of rocks: 1—high-grade ore; 2—cupriferous ore; 3—disseminated ore; 4—hornfel; 5—limestone.

It follows from Table 3 data that there is a strong correlation between the values of \((c^{**} - c^*) / c^*\) and \(\sigma_{\text{tcom}}^{\text{lim}} / \sigma_{\text{tens}}^{\text{lim}}\) at the correlation factor 0.954.

Regarding the change in the internal friction angle, a satisfactory correlation was observed with neither value of rock properties.

3. Conclusions

Based on the experimental data on strength characteristics of rocks (high-grade ore, cupriferous ore, disseminated, hornfel and limestone) sampled at a depth of 1600 m, it has been concluded that the values of limit strengths and moduli of deformation under triaxial compression at the lateral pressure of 5 MPa exceed the values of these characteristics under uniaxial compression by 40–80 and 30–60%, respectively; the values of Poisson’s ratio are lower by 10–40% in the latter case.

The difference in the values of cohesion obtained by two methods: Mohr’s envelope under tension and uniaxial compression and Mohr’s envelope under tension and triaxial compression (5 MPa) is from 11 to 18%; this difference in the values of internal friction angle—from 5 to 17%.

Both cohesion and internal friction angle calculated by the results of the tension and uniaxial compression tests are always less than these values calculated from the tension and triaxial compression tests for one and the same type of rocks. The values of relative change in cohesion in two specified methods and uniaxial/triaxial compression strength ratios obey strong correlation dependence at CF of 0.954. The revealed law can be used in calculations of cohesion of deep-level rocks.
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