The 56th International October Conference on Mining and Metallurgy
22-25 October 2025, Bor Lake, Bor, Serbia
www.ioc.tfbor.bg.ac.rs

DOI: 10.5937/IOC25052L
Original scientific paper

FAILURE CRITERION OF LIMESTONE AND GRANODIORITE DETERMINED BY LABORATORY TESTING AND THEORETICAL PROCESSING OF THE DRILLING PROCESS

Edita Lazarová[1a], Víťazoslav Krúpa[1b], Pavol Vavrek[1c], Mária Bali Hudáková[1d], Lucia Ivaničová[1e], Alexander Kiovský[1f]

[1] Institute of Geotechnics of the Slovak Academy of Sciences, Watsonova 45, 04001 Košice, Slovakia
[1a] lazarova@saske.sk, 0000-0003-4682-6433
[1b] krupa@saske.sk, 0009-0004-5030-0914
[1c] vavrek@saske.sk, 0000-0002-1125-1361
[1d] krulakova@saske.sk, 0000-0002-3897-4762
[1e] ivanic@saske.sk, 0000-0003-3844-9703
[1f] kiovsky@saske.sk, 0009-0002-7278-0360

Abstract

The results of experimental laboratory research on rock drilling, conducted with the use of diamond core bits, were processed mathematically. The developed theoretical models of rock resistance to disintegration facilitated the identification of three compatible views on calculating the ultimate stress state of rock drilled in the dynamic drilling mode with the use of diamond-embedded core drill bits. The contact surface strength of the rock σ_p [kN/mm], the dynamic cutting strength of the rock σ_μ [kN/mm], and the contact bulk strength of the rock σ_c [MPa] were defined. The strength values obtained from drilling into limestone and granodiorite were compared with the results of laboratory tests with the aim of identifying their uniaxial compressive strength, Brazilian tensile strength, punch shear, and Brinell hardness.

Keywords: *rock drilling, contact surface strength, cutting strength, laboratory testing*

1. INTRODUCTION

The ultimate stress state of rocks is determined by the conditions in which an external force, exerted on rocks, causes disturbance or disintegration of the rocks [1]. The existing experimental knowledge and empirical experience were used as the basis for the development of rock strength theories, micro-disturbance theories, crack propagation theories, and energetic and technological disturbance theories [2]. Relevant literature [3,4,5,6] presents models for the estimation of rock strength by investigating the interactions between the drill bits and the rocks; they are categorised into two groups: models based on the balance of forces; and models based on the balance of energies. This article presents the results of laboratory testing of limestone and granodiorite, as well as the results of the identification of rock resistance to disintegration, which was based on the theoretical processing of experimental drilling into limestone and granodiorite with the use of two diamond core drill bits with a diameter of 46 mm and the following diamond sizes: Drill Bit A (16/25 pcs.ct^{-1}); and Drill Bit B (25/40 pcs.ct^{-1}). The obtained values of strength of the drilled limestone and granodiorite samples were compared with the results of laboratory testing conducted with the aim of identifying uniaxial compressive strength, Brazilian tensile strength, punch shear, and Brinell hardness.

2. LABORATORY TESTING OF LIMESTONE AND GRANODIORITE

The testing of rocks, performed in the laboratory, is an important part of the engineering discipline of rock mechanics. The data needed for designing structures in rock-based materials (geotechnical engineering) is primarily gathered through testing, either in the laboratory or in the field. Much information can be obtained from laboratory tests of rock samples with a known orientation.

Laboratory tests usually consist of simple experiments that are appropriate to the nature of the rock, in which important quantities, often stress and strain, are determined. By drilling and cutting, the test samples of a regular shape were prepared from the individual rock types for the purpose of testing procedures compliant with the ISRM (International Society of Rock Mechanics) methodology, aimed at identifying the properties of the rocks. Their mechanical properties were determined using the INSTRON 1000RD testing machine, while the static Brinell Hardness (BH) was identified using the HDT-BRV 130 device. Bulk density ρ ($kg.m^{-3}$) at a natural moisture content was identified for cylindrical test samples with a diameter d = 54.4 mm. The aim of the uniaxial compression strength testing was to identify compressive strength of intact rock samples. Following the ISRM recommendations [7], the tests were carried out with cylindrical samples of regular dimensions with a height-to-diameter ratio of 2.0–3.0 and with a diameter of 54.4 mm.

Uniaxial compressive strength UCS (MPa) was identified by dividing the peak load P attained during the test to failure by the initial cross sectional area A. Tensile strength of rocks is usually defined as the maximum tensile stress that a particular rock mass can withstand. The Brazilian Test is a laboratory test conducted in rock mechanics in order to indirectly determine the tensile strength of rocks in MPa [8]. Hardness of a mineral and rock is its resistance to abrasion. Static hardness testing is based on rock indentation with the use of a hard tool. Hard metal balls or diamond cones or pyramids can act as indenters. The test load is applied with a defined initial application time and duration, and it has to be applied perpendicularly to the sample [9]. The Brinell hardness (kg/mm^2) test for limestones and granodiorites consisted of applying a constant load of 125 kg for a specified period of time (30 s) using a hardened steel ball with a diameter of 5 mm. For a punch shear τ_{ps} (MPa) test, flat rock discs are fitted into the testing jig [10]. The test is commenced by placing a rock sample at the bottom of the casing of a piston-shaped cylindrical jig having a puncher head which fits into a circular shear hole of another hollow cylinder. Then the puncher is placed in position and the entire device is placed in the compression-testing machine and loaded.

The results of laboratory testing of limestone are given in Table 1 and of granodiorite in Table 2.

Table 1. Properties of limestone

Statistical values	Bulk density	UCS	Brazilian test	HB	Punch shear
Number of samples evaluated	14	15	10	10	10
Mean	2 691	85.1	9.3	466.4	9.5
Median	2 691	77.8	9.5	457.1	10.0
Minimum	2 682	55.1	6.5	416.3	5.2
Maximum	2 702	119.2	10.8	521.8	14.2

Table 2. Properties of granodiorite

Statistical values	Bulk density	UCS	Brazilian test	HB	Punch shear
Number of samples evaluated	14	15	10	10	10
Mean	2,705	85.8	13.2	831.1	16.5
Median	2,706	85.4	13.1	873.9	17.7
Minimum	2,693	53.7	9.5	638.4	8.6
Maximum	2,717	122.3	16.9	927.6	24.3

The limestone specimens were taken from a quarry in Včeláre, located approximately 40 km southwest of the city of Košice – the centre of the Eastern Slovakia. The granodiorite piece specimens were taken from a quarry at Podhradová, located on the northern edge of the city of Košice.

2.1 Identification of rock resistance to disintegration

During the small-diameter drilling, the values of penetration depth p(F) and torque T(F) as a function of external force F were monitored. Equation (1), derived for calculating contact bulk strength of the rock σ_C, was as follows:

$$\sigma_C = \frac{F}{p(F)N\pi\overline{r_d}} \quad \text{(MPa)} \tag{1}$$

wherein the surface area of the contact surface between the drill bit and the rock is determined by the size (the diameter of spherical diamonds $\overline{r_d}$) and number N of diamonds and the penetration depth p(F). As the magnitude of the external force F changed, the penetration depth p(F) also changed. For the purpose of identifying σ_C, the drilling mode applied was the mode in which drilling is carried out at a minimum value of specific energy SE_{min}.

Contact surface strength σ_p (N/mm) was calculated using Equation (2):

$$\sigma_p = \frac{F_{inf}}{p_{max}} \quad \text{(N/mm)} \tag{2}$$

wherein F_{inf} is the external force in the inflexion point of the p(F) curve, and p_{max} is the maximum penetration depth. The cutting resistance of rock, which is a modification of the contact surface strength, is defined by Equation (3):

$$\sigma_\mu = Z.\mu.\sigma_p \qquad \text{(N/mm)} \tag{3}$$

wherein μ = cutting coefficient, calculated with the use of the torque value, and Z=3.351 is a derived constant applicable to drilling at the minimum value of specific energy. Table 3 and Table 4 present the calculated values obtained and processed with the use of data measured in the rotary small-diameter drilling into rock samples with the use of Drill Bit A and Drill Bit B. Each drill bit was used in drilling into limestone (L) and subsequently into granodiorite (G). After drilling into granodiorite, the drilling process was repeated alternately with limestone and granodiorite.

Table 3. Contact bulk strength and minimum specific energy

Drill Bit A	L_1	G_1	L_2	G_2	L_3	G_3	L_4
σ_C (MPa)	98.41	62.12	353.8	346.22	503.97	1059.2	717.73
SE_{min} (MPa)	1,072	734	3,561	3,366	5,046	6,540	6,128
Drill Bit B	L_1	G_1	L_2	G_2	L_3	G_3	L_4
σ_C (MPa)	89.44	79.32	376.4	252.31	487.68	236.92	393.96
SE_{min} (MPa)	1,056	984	4,102	2,714	4,855	2,737	4,033

Table 4. Contact surface strength and cutting strength

Drill Bit A	L_1	G_1	L_2	G_2	L_3	G_3	L_4
σ_p (N/mm)	7,343	4,635	26,400	25,830	37,600	79,030	53,550
σ_μ (N/mm)	6,356	4,478	19,260	20,000	27,210	40,000	34,390
Drill Bit B	L_1	G_1	L_2	G_2	L_3	G_3	L_4
σ_p (N/mm)	6,518	5,780	27,430	18,390	35,530	17,260	28,710
σ_μ (N/mm)	6,273	5,830	21,440	15,150	28,840	13,800	23,960

3. RESULTS AND DISCUSSION

As indicated by data in Table 1 and Table 2, limestone and granodiorite exhibited approximately the same uniaxial compressive strength (UCS). A more significant difference was observed for HB and τ_{ps} values. The calculated values of contact bulk strength σ_C (Table 3) for unworn diamonds are comparable to the UCS values. The greatest difference between limestone and granodiorite was observed in a comparison of their abrasiveness values. As for limestone, its abrasiveness value was identified as 0.0186 mg/m, while for granodiorite it was 1.4092 mg/m. Since granodiorite exhibited higher abrasiveness, as the drill bit wear increased, after the application with abrasive granodiorite, the values of rock resistance to disintegration also increased, while the same rising trend was observed for the values of specific energy. It means that the values of rock resistance to disintegration (as well as contact surface strength σ_p and cutting strength σ_μ, shown in Table 4) significantly increased due to increasing wear of diamonds. *(Note: The calculated values of σ_p and σ_μ for unworn diamonds were of the same order of magnitude as the values of Brinell hardness converted to MPa.)*

4. CONCLUSION

The defined values of rock resistance to disintegration significantly increased with changes in the condition of the rock-tool contact zone as the wear increased. Those changes were reflected in the values of specific energy. The presented laboratory tests with limestone and granodiorite were not affected by changes in the contact surfaces.

ACKNOWLEDGEMENTS

This research was supported by projects VEGA 2/0090/23 and APVV-23-0364.

REFERENCES

[1] E. Hoek, C. Carranza-Torres, B. Corkum, Hoek-Brown failure criterion – 2002 Edition. Proc. NARMS-TAC Conference, Toronto, 2002.
[2] Krúpa, V., Pinka, J.: Rozpojovanie hornín. TU Košice, 1997.
[3] S. Kalantari, H. Hashemolhosseini, A. Baghbanan, Int. J. Rock Mech., 104 (2018) 45–52.
[4] P. Kolapo, Geotech. Geol. Eng. 39 (2021) 1715–1726.
[5] C. R. Lakshminarayana, A. K. Tripathi, S. K. Pal, Int. J. Geo-Eng. 12, 23 (2021).
[6] Sh. Wang, Y. Wu, X. Cai, Z. Zhou, J. Cent. South University 30 (2023), 4036-4051.
[7] ISRM Commission on Standardization of Laboratory and Field Tests. Suggested methods for determining the uniaxial compressive strength and deformability of rock materials. September 1977.
[8] ISRM Commission on Standardization of Laboratory and Field Tests. Suggested methods for determining tensile strength of rock materials. March 1977.
[9] H. Konietzky, T. Fruhwirt, Overview about rock mechanical lab testing – part I: mechanical test. TU Bergakademie Freiberg, 2023.
[10] A.R. Jumikis, Rock Mechanics. Trans Tech Publications. First Edition, 1979.