Assessment of abrasiveness for research of rock cutting

Milan Labaš[1], František Krepelka and *Lucia Ivaničová*

Rock abrasiveness is ability of rock to wear down the working tool during the mutual interaction between the working indentor and the rock in the mechanical rock cutting process. The cutting indentor is worn down during the interaction, which changes its geometric dimensions causing the enlargement of a contact area between the tool and the rock surface. The changes in these dimensions consequently alter the rate of advance of the drilling machine and the specific cutting energy. We have determined the abrasiveness according to the norm ON 44 1121 (1982) on the testing device constructed at the Institute of Geotechnics SAS.

Key words: wear, rock abrasiveness, testing device

Introduction

Mechanical cutting of rocks, whether drilling or tunnelling, is substantially influenced by rock properties. Mechanical and technological properties of rocks affect the cutting process directly. Strength properties of rocks represent the dominant factors of mechanical properties. Indentation strength, showing good correlation with the cutting rate, is one of strength properties important for mechanical rock cutting. Technological properties of rocks are represented by hardness, drillability and rock abrasiveness. The cutting process is also affected by jointing of rock mass, particularly in such cases when the dimensions of the fracture are similar to the diameter of applied cutting tool. Rock abrasiveness immediately affects the wear of cutting indentors of the tool. The indentor wear exhibits in the decrease of the instantaneous drilling rate and in the increase of the specific cutting energy, which both directly affect the economical issues of mechanical cutting.

Rock abrasiveness represents the ability of rock to wear off the cutting indentors of the tool in process of mutual interaction of the working indentor and the rock in mechanical rock cutting.

As the cutting indentor is subjected to wear, which changes its geometric dimensions, the contact area between the tool and the rock surface is enlarged. Change of these dimensions leads to the change of the advance rate of the tool and the specific cutting energy.

Intensity and wear rate depend on several simultaneously acting factors in the interaction of the indentor and the rock. The most important factors:
1. type and properties of friction surfaces,
2. operation regime of the cutting indentor (combination of input variables of cutting process),
3. properties of the environment where the indentor operates.

Abrasion can be defined as the wearing or tearing away of particles from the surface of indentor. Abrasion is a global effect of physical and mechanical rock properties in contact with the cutting indentor. As the tool properties are considered in the tool-rock interaction, rock abrasiveness is a feature that depends on the condition of the cutting indentors. Due to this fact, the effect of the indentor properties has to be eliminated during the determination of the rock abrasiveness by laboratory methods. Selection of one type of the indentor with predefined physical and mechanical properties for laboratory testing, delivers the results of abrasiveness, characterizing a particular rock type. Environment, where the interaction takes place, also affects the process of mutual interaction between the indentor and the rock. The effect of environment is not negligible; therefore a stable environment in laboratory conditions has to be ensured in order to eliminate its systematic effect on global results, mainly during the abrasiveness testing of various rock types.

Methods for abrasiveness assessment

There are several methods for estimating the abrasiveness of rocks and minerals, used with various degrees of success and relevance. They can be broadly divided into three categories (Golovanevskiy, Bearman, 2008):
1. Holistic approaches - abrasiveness assessment via a combination of fundamental rock properties and many varied process parameters and environmental conditions.

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[1] *Ing. Milan Labaš, PhD.,. Ing. František Krepelka, PhD.*, *Ing. Lucia Ivaničová, PhD.*, Institute of Geotechnics of the Slovak Academy of Sciences, Watsonova 45, 043 53 Košice, Slovak Republic, labas@saske.sk, krepelka@saske.sk, ivanic@saske.sk

2. Indirect methods - abrasiveness assessment through a combination of hardness, compressive strength and other fundamental rock properties.
3. Direct methods - abrasiveness assessment from test methods where there is a relative movement of rock sample and wear tool in contact under standard controlled test conditions.

The holistic studies take into account the effects of machine scale, wear surface structure, size distribution of particles, mechanical properties of the rock, changes of the wear regimes, the effects of temperature and moisture etc. The holistic approaches to rock abrasiveness assessment are specific to certain equipment or processes and therefore of limited value for other applications.

The indirect methods of rock abrasiveness assessment have the advantage of using data, which is either readily available or relatively straightforward to obtain. However, they do not take into account process variables for specific modes of wear. Indirect measurements assessed rock abrasiveness through standard mechanical property tests such as Schmidt hammer, Shore scleroscope, the cone indenter tests, unconfined compressive strength, indirect tensile strength, rock hardness and toughness or Vickers hardness test, the Mohs hardness scale and the volume ratios of different minerals in the rock.

The direct methods of rock abrasiveness assessment use standard conditions to determine rock abrasiveness in a specific mode of wear, either low or high stress, or impact abrasion. The tests examine the effects of relative movement of a rock sample and a wear tool in contact. These tests use loading applied to a rock sample either statically or dynamically, under a low sample/wear tool relative speed and in many instances they employ low impact abrasive conditions.

Abrasiveness tests used nowadays for rock and soil testing are divided into three groups (ISRM) (Krepelka et al., 2000):
1. Impact tests – Los Angeles test, sand test, Burbank test;
2. Pressure tests – Dorry test, ASTM 2-241-51 test, modified Dorry test, drill tests, Taber Abraser Model 143;
3. Abrasion tests – Deval test.

Los Angeles test measures abrasiveness as a result of the impacts of rock chips and a dose of steel balls in rotating drum. Sand test involves steel blades from tested alloy rotating (632 rpm) inside the drum containing rock samples, with drum rotating at 74 rpm.

Dorry test, ASTM 2-241-51 test and modified Dorry test use rock sample pushed against the rotating steel disk with abrasive medium (quartz sand, powder Al_2O_3) added onto the contact surface. Drill tests determine the wear of drilling bit in certain time interval or per drilled length in defined conditions. Taber Abraser Model 143 provides testing of 6 mm thick rock disk from the NX core rotating 400-times under a metal wheel loaded by weight of 250 g. The loose debris is removed by a vacuum system. Rock weight loss is a measure of a resistance of rock to abrasion and the weight loss of the steel wheel is a measure of the rock abrasiveness. The test is used for drillability prediction for tunnelling machines.

Deval test involves rock chips milled slowly in the Los Angeles drum, but without the steel balls. Only the abrasion resistance of rock is determined, not the rock abrasiveness.

Following tests are used commonly to assessment of the rock abrasiveness for the purposes of mechanical rock cutting by drill bits and roller discs:
1. The Cerchar test,
2. The LCPC abrasimeter test,
3. The NTNU abrasion test,
4. The gouging abrasion test.

The Cerchar test determines the abrasiveness of natural rocks, by measuring the wear on a steel cone, caused by scratching a freshly broken rock surface. The method was developed at CERCHAR (Centre d'Études et Recherches des Charbonnages de France). Cerchar abrasivity index (CAI) testing has been recommended by International Society of Rock Mechanics (ISRM) as a suggested rock mechanics testing method (Yarali et al., 2008) for excavability, drillability, and cuttability of rocks. Two types of testing devices are in use today: the original layout entitled as Cerchar apparatus and the testing device entitled as West apparatus (Fig. 1) (Plinninger et al., 2003). The original layout (Fig. 1, left) mainly features a vice holding the rock specimen and a testing lever that is directly connected to the steel pin. The steel pin is loaded with a static force of 70 N. In this testing setup, the steel pin is scratched over the rock surface by moving the lever at a velocity of 10 mm.s^{-1}. The West apparatus (Fig. 1, right) also features a vice and a steel pin loaded with 70 N. In contrast to the Cerchar apparatus, the testing velocity is slower, taking 10 s for the 10mm scratching distance. This is due to the different movement control, which is performed by a hand crank that moves the rock sample below the pin. The Cerchar test gives Cerchar Abrasivity index

(CAI). Ignoring the effect of varying testing velocities, the CAI values derived from both types are estimated to be equal. The Cerchar abrasiveness index (CAI) is calculated as a mean value of 2 - 5 individual tests from the needle wear flat diameter. A detailed evaluation of the needle wear flat should be made by microscopic analysis. The Cerchar index scale ranges from 0 to 6, one index point corresponds to a conic blunt surface diameter of 0,1 mm. Plinninger et al (2003) suggested some modifications of the Cerchar test based on testing experience. They suggested five individual tests for every rock sample to achieve a better defined mean value. Sample preparation with diamond rock saws is recommended for inhomogeneous rock types to achieve even rock surfaces. These values can then be compared with standard CAI values achieved on rough surfaces by using the empirical equation. Although the recommendations suggest only the use of pins made from 115CrV4 tool steel hardened to a Rockwell Hardness HRC of 54–56 and a tensile strength of about 2000 MPa.
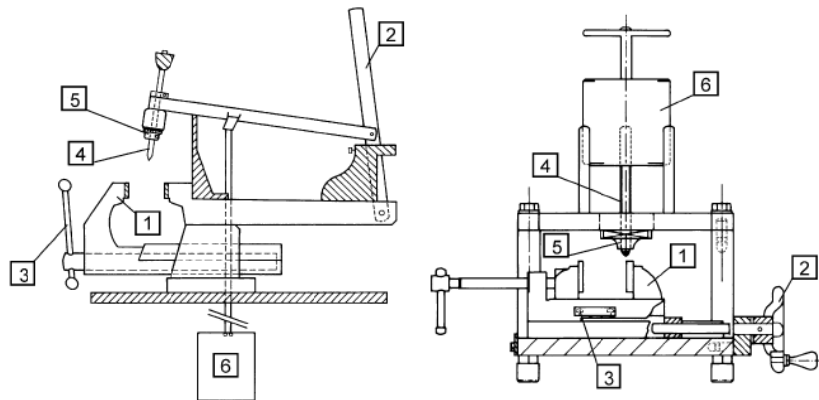

Fig. 1. Testing devices to determine the CERCHAR abrasiveness index. (Left) CERCHAR apparatus: 1+3-sample vice; 2-hand lever; 4-testing pin; 5-pin chuck; and 6-weight. (Right) West apparatus: 1-sample vice; 2-hand crank; 3-vice sled; 4-testing pin; 5-pin guide; and 6-weight (Plinninger et al., 2003).

The LCPC Abrasimeter Test involves the taking of samples of rock, soil or synthetically created materials and testing using the 4 mm – 6,3 mm fraction. The method was developed at LCPC (Laboratoire Central de ponts et Chaussées, France). Coarser material has to be crushed and sieved. The LCPC abrasivity-testing device is built of a motor holding a metal propeller rotating in cylindrical vessel (ø 93 mm x 100 mm) containing the granular sample (Fig. 2) (Thuro et al., 2006). The air-dried sample of the fraction 4 – 6,3 mm (500 ± 2 g) is poured into the cylindrical container through the funnel tube. The rectangular metal propeller of the size 50 x 25 x 5 mm rotates for 5 minutes at a speed of 4500 rpm in the cylindrical container with a sample material. The standardized metal hardness of the test propeller is given as Rockwell B 60 – 75. The propeller is weighted before and after the test. The mass loss of the metal propeller is a measure of the sample abrasiveness. The LCPC test gives the LCPC abrasivity index – ABR. The coefficient ABR (g.t^{-1}) is calculated in g of loss in weight of the metal test propeller per t of sample material. The coefficient ABR is extremely low for soft, slightly abrasive rock and amounts to more than 1500 g.t^{-1} for very hard and abrasive rock.
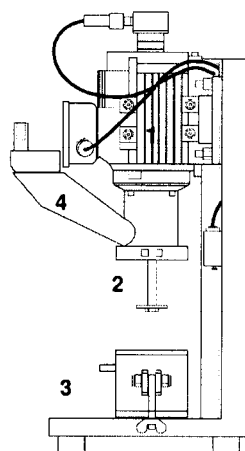

Fig. 2. LCPC abrasivity-testing device: 1- motor, 2 – metal propeller, 3 sample container, 4 – funnel tube (Thuro et al., 2006).

NTNU abrasion test is a methodology for estimating the drillability of rocks by percussive drilling and was developed at the Engineering Geology Laboratory of the Norwegian Institute of Technology (NTH) (later renamed to NTNU – Norwegian University of Science and Technology) (Nilsen et al., 2007). Abrasion testing of crushed rock particles <1.0 mm, as illustrated in Figure 3, was then introduced together with the Brittleness test and the Sievers-J miniature drill test for estimating the drillability parameters DRI (Drilling Rate Index) and BWI (Bit Wear Index). Later the tests have been used mainly for predicting hard rock TBM wear performance according to the method developed by the NTH. For TBM cutter wear prediction, a test piece of steel taken from a cutter ring is used instead of the tungsten carbide test piece used for percussive drilling estimation, and the parameter CLI (Cutter Life Index) is calculated instead of BWI. The Abrasion Values AV/AVS represent time dependent abrasion of tungsten carbide/cutter steel caused by crushed rock powder. The same testing equipment as for the AV is used to measure the AVS. The two tests are defined as follows:

AV - The Abrasion Value is the mean value of the measured weight loss in milligrams of 2–4 tungsten carbide test bits after 5 minutes, i.e. 100 revolutions of testing, by using the abrasion apparatus and crushed rock powder.

AVS - As described for AV, but with 1 minute, i.e. 20 revolutions of testing.

The new NTNU Soil Abrasion Test (SAT) is a further development of the existing abrasion tests for soils. Compared with the AVS test only one detail has been changed: instead of crushed rock powder <1 mm a sieved soil sample <4 mm is used in the SAT test.
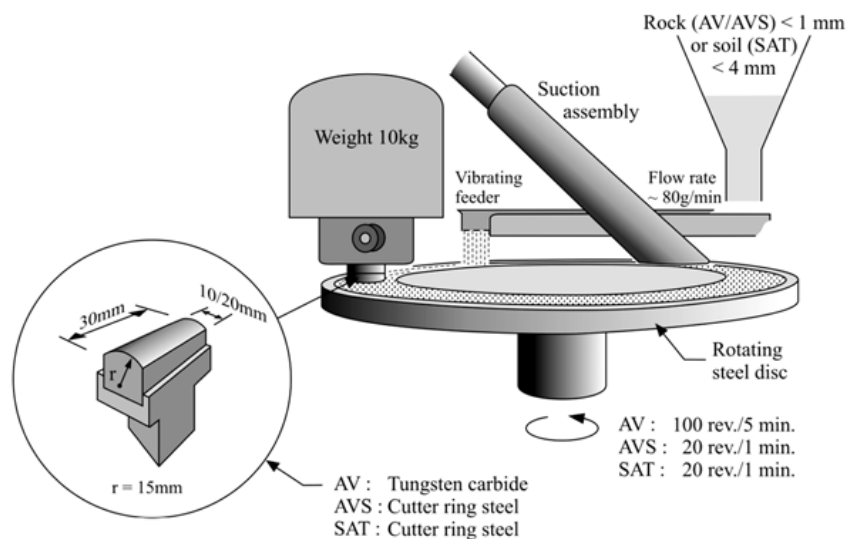

Fig. 3. Principle scheme of the NTNU abrasion tests (Nilsen et al., 2007).

The Gouging Abrasion test simulates very high stress abrasion under high-energy impact conditions (Golovanevskiy, Bearman, 2008) and was developed at Advanced Manufacturing Technologies Centre (Australia). The testing is performed as follows. A flat rectangular rock sample is placed into a sample holder. A steel wear tool with a 90° sharp conical point is affixed to the swinging pendulum arm of the tester and the arc of the pendulum travel is adjusted so that the wear tool forcibly contacts the surface of the rock sample as it swings past. The design of the test apparatus for Gouging Abrasion testing is shown schematically in Fig. 4. The rock specimen is held in the sample holder, 1. The sample holder can be moved vertically using the transmission screw assembly, 2, and horizontally across by the spring-loaded mechanism, 3. A wear tool, 4, is rigidly positioned in the wear tool holder, 5, of the pendulum arm, 6. The pendulum arm is released from its working position and the tip of the wear tool is applied to the surface of the rock specimen on the downward swing of the pendulum arm. The test samples are rectangular 80±0.5 mm long, wear surface of the samples is flat and smooth as normally achieved by wet circular cutting with a diamond-tipped masonry blade. The wear tools are made from steel heat treated to Rockwell hardness 40/42 HRC. Similar to the methodology for calculating the abrasiveness for the Cerchar test, Gouging Abrasion Index (Gi) is calculated as the mean average of the wear flat diameter of the wear tools in millimetres multiplied by a factor of 10. Each of the rocks is tested three to five times. Values of Gi varied from 0,5 to 22 for tested Australian rocks (Golovanevskiy, Bearman, 2008). The results of testing can be used for wear rates predictions of crushers, wear liners in hoppers and chutes, ground engaging tools and discs of tunnel boring machines.
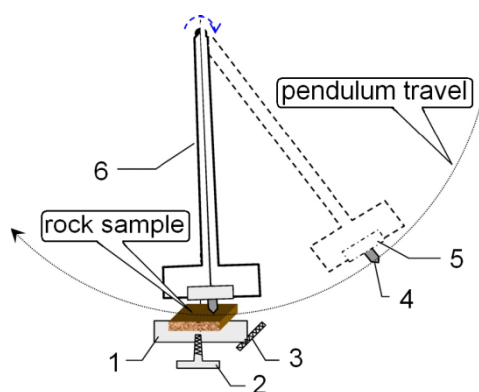
Fig. 4. Gouging abrasion test setup (Golovanevskiy, Bearman, 2008).

Method of the assessment of rock abrasiveness according to ON 441121 norm

One of the methods for rock abrasiveness testing is the method according to the ON 441121 norm. The concept of the test resides in the determination of weight loss of normalized testing body (metal pin) during its circular motion on a treated surface of a tested rock sample under constant thrust force related to total track length of the tested body.

Testing device (abrasionmeter) for the ON 441121 test is a rotating machine with constant revolutions 100 rpm, which provides a constant thrust force 100 N during the whole testing period and registers the revolutions with a possibility to stop after reaching the predefined number. The structure of the device is illustrated in the Fig. 5. Testing requires a set of normalized metal pins (number of pins relates to the number of tracks) of 3,0 mm diameter, 22 mm length, 720 MPa strength and 210 HB hardness. Tested rock bodies are prepared from the rock sample by treating the samples into one or two wheel samples with minimal diameter 59 mm. Proper samples are prepared of a drilled rock core. Tested surface has to be orthogonal to the longitudinal axis of the body and has to be roughed by quartz sand with 0,6 to 1 mm grain size in order to eliminate the treating effect, i.e. the surface should show a character of natural surface of rock fracture (roughening is done by a motion of tested body in quartz sand with thrust 80 N and track long 8 – 10 m).

Tested rock body is placed centrally into the fixing jaws of the abrasionmeter keeping the measured surface vertical and orthogonal to the axis of the installed normalized metal pin.

The set of metal pins is weighted altogether and then fixed one after another into the slider of abrasionmeter. The measurements are taken subsequently on the concentric tracks with diameters of 10, 20, 30, 40 and 50 mm (with individual pins) at constant thrust 100 N and defined number of revolutions n=32. The measurement is finished when the metal pins perform a total track 15,08 m long. The set of pins is cleared from the residues (products of abrasion) and weighted altogether by the analytic balance with accuracy 1/10000 g and the total weight loss is calculated for a whole set of pins used for one rock sample. Smaller rock samples that does not meet requirement of concentric tracks with diameters from 10 up 50 mm can be tested too. Two samples are than tested on the concentric tracks with diameter of 15 and 25 mm at number of revolutions n=30. The requirement of total track 15,08 m must be fulfilled. Then the abrasiveness F_V of tested rock body is calculated after a formula:

$$F_V = \frac{G}{L} \qquad [mg.m^{-1}] \tag{1}$$

where F_V is the rock abrasiveness, G is a sum of weight loss of the set of metal pins (mg), L is a total track of motion (15,08 m).

Figure 5 shows a design of abrasionmeter constructed according to ON 441121.

Rocks are divided into three groups according to the FV value (Exner, 1988):
Lowly abrasive - FV < 1 mg.m-1,
Moderately abrasive - FV = 1 – 3,5 mg.m-1,
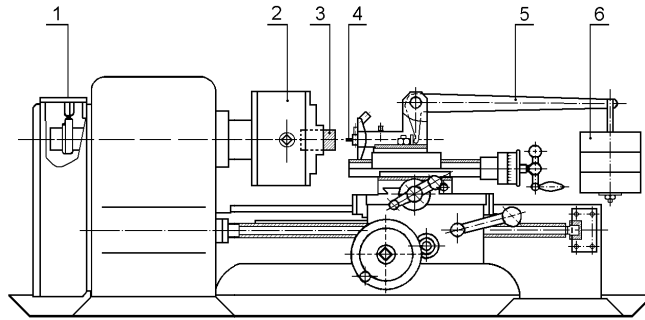Highly abrasive - FV > 3,5 mg.m-1.

Fig. 5. Design of abrasionmeter according to ON 441121: 1 – revolutions counter, 2 – chuck for fixation the tested rock body, 3 – tested rock body, 4 – metal pin, 5 – lever gear for constant thrust, 6 – balance weight, 7 – suction of residues.

At present, there is no commercial device (abrasionmeter) for the rock abrasiveness assessment according to the ON 441121. The first prototype of the abrasionmeter designed at the Institute of Geotechnics was based on a drill press, so the orientation of a rock sample and position of the acting pin were vertical. Another type of abrasionmeter was constructed later due to problems with control and sample and pin manipulation. Next prototype based on the presented design of an abrasionmeter was constructed at the Institute of Geotechnics of Slovak Academy of Sciences (Fig. 6) by the adjustment of a turning lathe enabling continuous setting of revolutions ranging from 20 up 2500 min^{-1}. A lever gear providing constant thrust was installed on the lathe. Measurement is controlled by a control unit consisting of a counter of impulses with a switch and of an induction gauge for counting the revolutions.
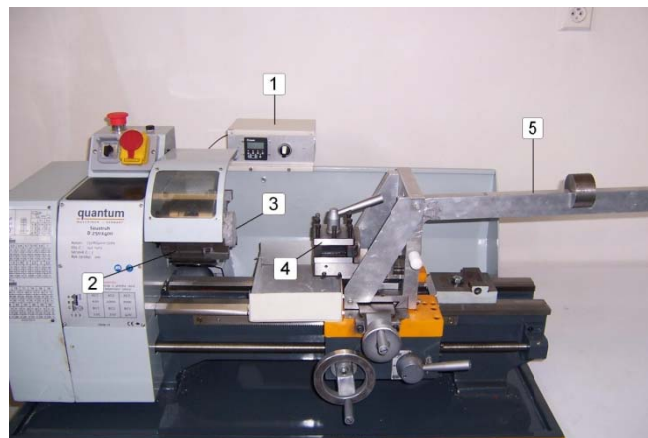

Fig. 6. Abrasionmeter constructed in the Institute of Geotechnics SAS: 1 – control unit, 2 – chuck for fixation of tested rock body, 3 – tested rock body, 4 – holder of metal pin, 5 – level gear for constant thrust.
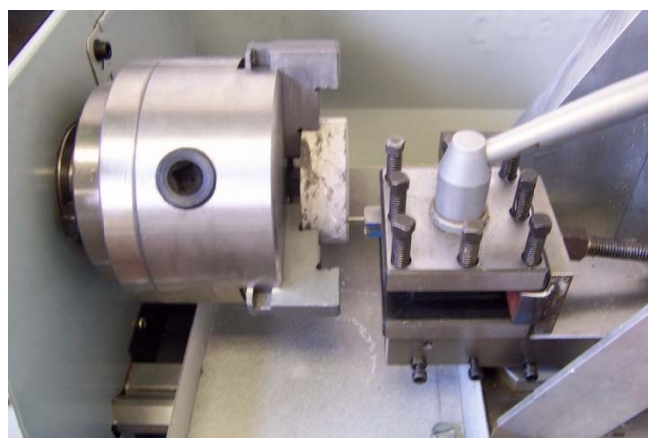

Fig. 7. Details of a rock sample in the fixing jaws and the acting pin.

Results and discussion

The aim of the experiments was to verify a repeatability of abrasiveness assessment on the abrasionmeter. Two different types of rocks were chosen, the limestone from Včeláre site and the granite from Hnilec site. The limestone is compact, fine-grained rock, without fracturing and it can be assigned as homogeneous. The Hnilec granite is porphyritic rock with grain size up to 3 mm. Abrasiveness was measured on 9 limestone samples and 13 granite samples. Abrasiveness values of other rock types were assessed as well; abrasiveness measurements were performed on 3 samples of each rock type. The results of abrasiveness measurement are presented in the table 1.

Tab. 1. The abrasiveness values according to the ON 441121 norm for several rock types (* - 4 different facies).

Rock type	Abrasiveness F_V, [$mg.m^{-1}$]
granite (porhyritic, Hnilec)	1,0264
limestone (compact, Včeláre)	0,0186
andesite (slightly weathered, Ruskov)	0,7913
granodiorite (Ťahanovce)	1,4092
gneiss (Ťahanovce)	1,4609
limestone (Važec-Dúbravy) *	0,0508
limestone (Važec-Dúbravy) *	0,0729
limestone (Važec-Dúbravy) *	0,0707
limestone (Važec-Dúbravy) *	0,5393

The rock samples used in abrasiveness measurement are presented in Fig. 8. The black concentric tracks are only visible on samples of rocks with higher abrasiveness (granodiorite, gneiss). These tracks are created by abrasion of steel pins on the rock surface. In the case of limestone with a small abrasiveness value, the tracks with the depth up to 1 mm are created and no visible steel particles are present.

Fig. 8. Rock samples after testing, from left: granodiorite and limestone with five concentric tracks and a smaller sample of gneiss with two tracks.

The frequency diagrams of abrasiveness values assessed according to the ON 441121 norm ("F_V abrasiveness") are presented in Fig. 9.
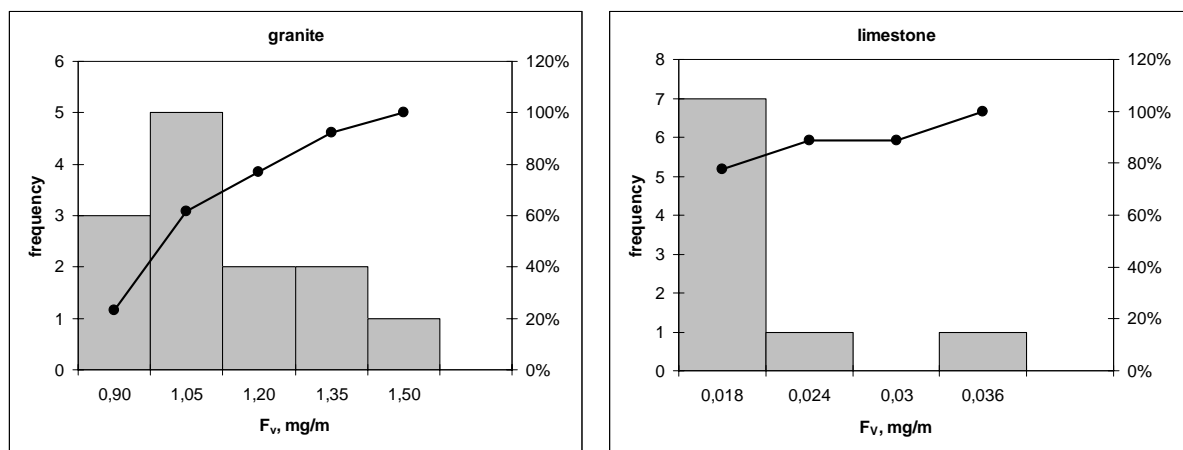

Fig. 9. Frequency diagrams of FV abrasiveness values for granite and limestone.

All abrasiveness values are in the first class interval and only two values are out of the interval in case of limestone. One value is clearly right, which is either an effect of some anomaly in rock structure or it is a measurement error. Distribution of F_V abrasiveness values is clearly right-skewed for the granite. This is conformable to Weibull distribution, frequently used for description of rock strength parameters distribution.
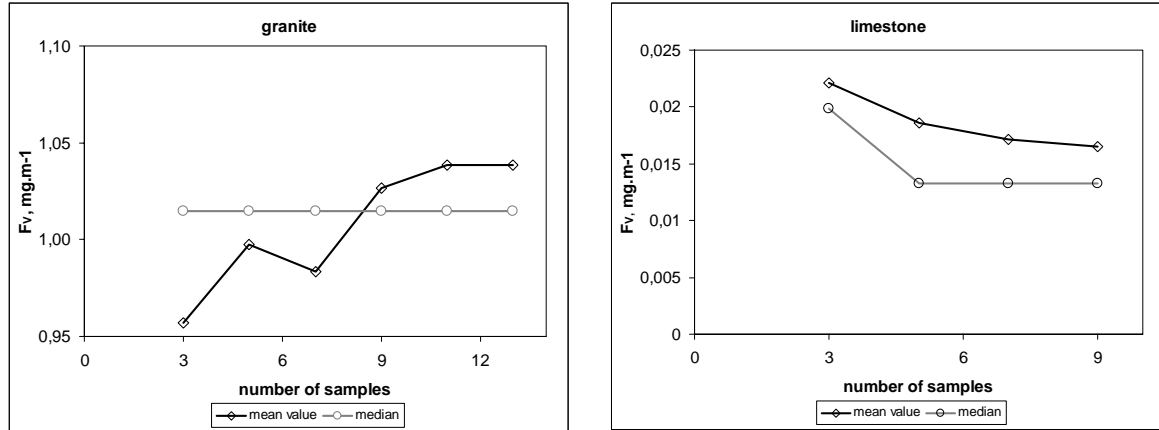

Fig. 10. Mean values and median values of the FV abrasiveness (ON 441121).

The mean values and values of median of the F_V abrasiveness of the granite and the limestone are presented in Fig. 10. Stabilization of the mean value is evident with the increasing number of samples for both rock types. Median is nearly constant or constant. Median is so called robust position criterion and the appreciable change of some values can be negligible. The mean value does not show such attribute.

Values of the standard deviation for both rock types are presented in Fig. 11. The stabilization of standard deviation values is apparent. The change of standard deviation for limestone after ignoring the extreme value (Fig. 9) appears very interesting.
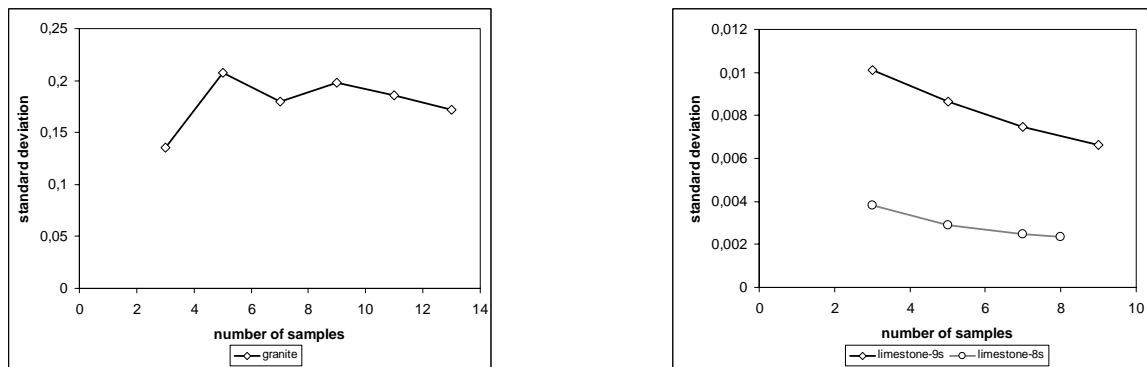

Fig. 11. Values of standard deviation of FV abrasiveness for the granite and the limestone, limestone-9s – 9 samples, limestone-8s – 8 samples without an extreme value.

Conclusion

The method and results of assessment of F_V abrasiveness according to the ON 441121 norm were presented in the paper. The abrasionmeter of Institute of Geotechnics is a very adaptive system, any changes in the method (change of thrust, rotational speed, pin quality, total measurement path, etc.) can be easily adjusted. The results of measurements indicate some recommendations for this method. Measurements have to be made with at least 3 samples for homogeneous fine-grained rocks and 5 samples for heterogeneous rocks. In the case of extreme result occurrence, the measurement has to be repeated. Measurements with the abrasionmeter are dynamic (in contrast to Cerchar test), they accept the requirements of physical modelling (scale effect in relation to the rock surface quality and the pin dimension) and sample preparation is simple (in contrast to LCPC and NTNU tests). However, larger sets of measurements have to be performed

and compared to other methods, evoking a discussion on rock abrasiveness determination for the purposed of rock cutting by drilling and tunnelling, similarly to discussion provided by Plinninger et al (2003).

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