Acta Montanistica Slovaca
ISSN 1335-1788
actamont.tuke.sk

Experimental investigation of specific energy and wear intensity of diamond-impregnated core bits in rock drilling

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Funding information:
VEGA 2/0090/23 APVV 23-0364

Acknowledgement: This work was supported by the project VEGA 2/0090/23 and APVV-23-0364.

How to cite this article:
Lazarová, E., Krúpa, V., Bali Hudáková, M., Kiovský, A., Vavrek, P. and Ivaničová, L. (2025). Experimental study of specific energy and wear intensity of the diamond-impregnated core drill bits. *Acta Montanistica Slovaca,* Volume 30 (2), 432-440

DOI:
https://doi.org/10.46544/AMS.v30i2.13

Abstract
Drilling is one of the most important and expensive geological survey processes. The wear of drill bits is closely related to the specific energy that expresses the energy consumption of the drilling process and significantly affects the total cost of drilling. In this article, the correlation between the wear intensity and the specific energy was examined. For the purpose of obtaining the necessary information, a series of experiments were performed on a horizontal laboratory drilling rig with the use of 8 types of rocks and 5 diamond-impregnated small-diameter core drill bits with synthetic diamonds of various qualities. The selected drilling mode was the mode with a constant rotation speed and an increasing thrust force. Results of the experimental measurements indicated that relatively high rotation speeds were preferred for the tested drill bits for the purpose of efficient drilling. The lowest amount of the specific energy required for drilling was observed for sandstone and andesite, i.e. the rocks in which radial cracks were formed around the chipped-off crater during the drilling. A simple linear regression between the intensity of wear of the drill bits and the specific energy was found. The evaluation of the results of this experimental research also showed that the quality of the used diamonds significantly affected the wear intensity.

Keywords
Rotary rock drilling, rock, diamond impregnated core drill bit, drill bit wear, specific energy

Introduction

The purpose of this research was to investigate the process of rotary drilling of rocks using small-diameter diamond core drill bits used in the mining industry, civil engineering and geology for geological exploratory drilling.

The core drilling process consists of three stages – drilling, retrieving the core sample, and resuming the drilling. Drilling is a complex process that is affected by several factors and may be divided into three categories: 1. Parameters related to a drilling set and a drilling tool; 2. Parameters related to the rock properties; and 3. Technical and operational parameters (Kolapo, 2020; Sakız et al., 2021). The combined effects of those parameters on the drilling performance create complicated conditions that are difficult to effectively evaluate and predict (Li et al., 2020).

A drill bit fixed to a drill rod provides the transfer of energy from the drilling equipment to the rock. During the drilling, it rotates and is subject to a load/force exerted in the direction of the drilling axis (also referred to as the weight on bit – WOB). The force significantly affects the wear of the drill bit. In general, wear is directly proportional to the exerted load. The drill bit, as such, does not represent the high cost of drilling. However, replacing a worn or damaged drill bit is a long process and is considered the key factor determining the cost-efficiency of drilling (Mazen et al., 2020).

Possessing the information on the real condition of a drill bit is the key precondition for its further use. The evaluation of the drill bit's condition mostly depends on the human factor, while the experience of the operating staff has a significant effect on the evaluation accuracy. There is still no comprehensive universal method that would facilitate the timely replacement of drill bits. Multiple diagnostic methods have been developed and used with more or less success to monitor the degree of wear and identify the real condition of drill bits. In general, they may be categorised as direct and indirect measurement methods. In a direct measurement, the sought parameter value is identified directly by a measurement. In an indirect measurement, the sought parameter value is calculated using an equation describing the relation between the parameter and the parameters identified directly by measurements. The suitability of the methods depends on the required accuracy, available time and funds, as well as the purpose of the measurement (Cooper, 2002). In this paper, the direct measurement method was applied with the aim of determining the values of wear of the tested drill bits.

Drill bit wear is closely related to the energy consumption of the drilling process (Mostofi et al., 2018). The quantification of energy consumption was carried out using the specific energy. It expresses the energy necessary to break a unit volume of rock during the drilling. In order to increase the energy efficiency of the drilling process, the amount of energy required for the drilling should be subjected to evaluation already during the drilling process (Meng et al., 2012). Several studies have been conducted in order to predict and calculate specific energy using various operational parameters of the drilling process and various rock properties (Al-Sudani, 2017).

Research into the mechanism of drilling with impregnated diamond drill bits has been described in multiple studies (Borri-Brunetto et al., 2003; Miller& Ball, 1990; Mostofi et al., 2013; Xuefeng & Shifeng, 1994; Song et al., 2022). In the research presented in this paper, values of specific energy were evaluated for impregnated core drill bits with diamonds of various qualities with the use of various applied operational parameters (rotation speed and thrust force). The minimum value for specific energy was defined based on the identification of the value of optimal thrust force F_{opt} from the derived mathematical models. The correlation between specific energy and the calculated wear intensity was analysed on eight types of rock samples. Results of the tests performed on five impregnated diamond drill bits with diamonds of different qualities confirmed that the quality of diamonds affects the wear intensity.

Experimental part

This research focused on the study of the mechanism of mechanical rock cutting by rotary drilling. To obtain the necessary information, a series of experiments was performed on a horizontal laboratory drilling rig using different rock types and impregnated diamond core drill bits of various concentrations, sizes and qualities of the diamonds.

Experimental equipment

The test equipment for simulating the drilling process without the impact of the drill string was constructed at the Institute of Geotechnics of the Slovak Academy of Sciences. It is intended to investigate the effects of different drilling modes on the rock disintegration and the wear of drill bits, investigate the drillability of rocks and the energy requirement for the drilling process, and assess tested drilling tools in terms of their applicability in real operational conditions.

The laboratory drilling rig is equipped with a measuring system that controls the experiment and facilitates continuous measurements of the parameters related to the drilling process. The actual operation of the drill rig is ensured by an industrial PLC computer (Programmable logic controller). In the automatic mode, it is controlled by a computer. The measured data are sent to and stored on the archiving server. The diagram illustrating the rig control mechanism is presented in Fig. 1.

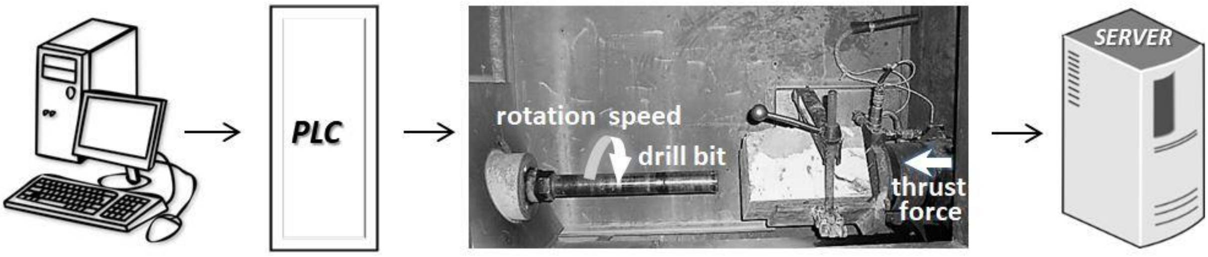

Fig. 1. Laboratory drilling rig control diagram

The rotation speed of a drilling tool may be adjusted by regulating the electric drive unit. The thrust force exerted on the rock may be continuously regulated and measured by means of a pressure cell on the hydraulic cylinder. The drilled depth is measured by a magnetostrictive linear position sensor Baluf BTL7 installed on the hydraulic cylinder. Torque and 3 orthogonal components of the cutting force are measured by a 4-component dynamometer Kistler 9272. On the frame for fixing the test rock samples are 3 perpendicularly fixed piezoelectric vibration sensors of different sensitivities and resonant frequencies, supplemented with the Adash 3900-II online vibration monitoring system. Using a hose attached to a water pump, drilling fluid is supplied to the drill bit at a constant flow rate of $10^{-3}.m^3.s^{-1}$. Experimental samples are blocks with the dimensions of approximately 150x150x300 mm. The terminal switch for measuring the position facilitates the drilling of up to 260 mm of the sample. The scheme of the basic concept of the control and measurement components of this experimental equipment is shown in Fig. 2.

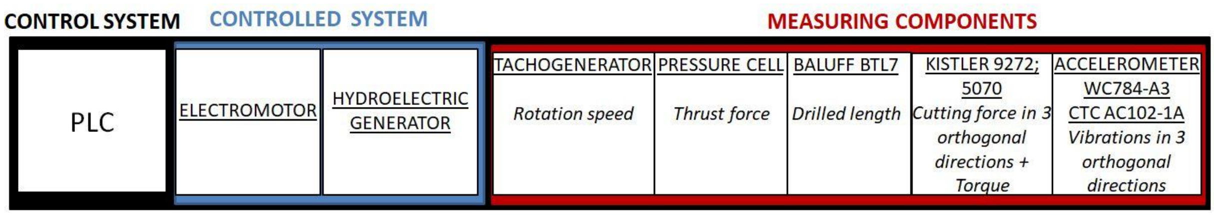

Fig. 2. Control and measurement components of the experimental equipment

Tested impregnated core drill bits

Five impregnated core drill bits were tested and analysed in the present experimental research. Each drill bit had 8 channels for supplying drilling fluid during the drilling process to remove the chips of the drilled rock from the cutting zone. The matrix of the drill bit contains synthetic diamonds of various concentrations, qualities and sizes. The concentration of diamonds on the surface affects the wear of the matrix. With a higher concentration of diamonds, the matrix is better protected, and hence, the service life of the drill bit is prolonged (Guttenkunst, 2018). Three different types of diamonds were used: synthetic diamonds produced by Czech companies DSK-E and DSK and synthetic diamonds produced by DeBeers SDA-85. The diamonds differed in quality and grain size. The designations and other parameters of the used drill bits are listed in Tab. 1 below.

Tab. 1. Parameters of the tested impregnated drill bits

Number of cutting segments: 8	Drill bit designation	**IS-1A**	**IS-1B**	**IS-2**	**IS-3A**	**IS-3B**
	Mesh size	50/60	40/50+50/60	50/60	40/50	40/50
	Grain size [mm]	0.3–0.25	0.42–0.3+0.3–0.25	0.3–0.25	0.42–0.3	0.42–0.3
	Quality of diamonds	DSK-E		DSK-S	SDA-85	
		low		medium	high	
	Drill bit diameter [mm]	46				
	Matrix hardness [HV]	300				

Tested rocks

In this research, drilling was carried out into eight types of rocks – andesite, granite, greisen, diabase, sandstone originating in two locations, and dark and bright slate. The tested rocks had different origins and compositions and different mechanical and technological properties. Tab. 2 shows the classification of the tested rocks, specifically created based on their genesis, drillability, abrasiveness and strength. Classifying rocks into individual classes was based on our knowledge and experience gained while drilling on the experimental drilling rig using impregnated diamond drilling tools.

Tab. 2. Classification of the tested rocks

Rock	Location	Origin	Drillability	Abrasiveness	Strength
Andesite	Ruskov - SR	Magmatic	Easy	Moderate	IV
Granite	Hnilec - SR	Magmatic	Moderate	High	III
Greisen	Hnilec - SR	Metamorphic	Moderate	High	III
Diabase	Hnilec - SR	Magmatic	Difficult	Moderate	II
Sandstone	Řeka - CR	Sedimentary	Easy	High	I
Sandstone	Čergov - SR	Sedimentary	Easy	Moderate	II
Dark slate	Jeseníky - CR	Metamorphic	Moderate	Moderate	II
Bright slate	Jeseníky - CR	Metamorphic	Moderate	Moderate	II

As to the technological properties, the one that is important for drilling is drillability. It expresses the resistance of rock to external destructive forces. It is affected by the strength of the rock, its fracture ability, a degree of tectonic disturbance, a degree of weathering, and grain size. Another parameter of the technical characteristics of rocks that affect drilling is abrasiveness. The abrasiveness of the tested rocks was identified following the ON 44 1121 standard (1982) on the test equipment constructed at the Institute of Geotechnics. The concept of the test resides in determining the weight loss of a normalised testing body (metal pin) during its circular motion on a treated surface of a tested rock sample under a constant thrust force related to the total track length of the tested body. Higher fracture ability and larger grain sizes cause the rock to be more abrasive for the drill bit. Fine-grain, hard rocks are less abrasive. The strength-related classification of the rocks was based on the test of uniaxial compressive strength performed on the test press following the applicable technical standards. The values were identified under the indenter's slow and evenly distributed pressing into the cylindrical rock samples obtained from drill cores. The strength of rocks decreases with weathering, and such rocks cause less wear to the drill bit.

It should be noted that rock, regardless of its homogeneity level, is an anisotropic material with locally changing properties, which is also manifested while it is being disintegrated.

Experiment methodology

Experimental drilling was carried out on the laboratory drilling rig. The drilling experiments were performed at a quasi-constant flow rate, and the quantity of the drilling fluid was sufficient for cleaning the front side of the drilled surface. Several series of experiments were carried out. Each series of experiments consisted of drilling into all of the tested rocks using an impregnated core diamond drill bit at a constant rotation speed (500; 1,000; 1,500; and 2,000 rpm) and at an increasing thrust force.

For research purposes, the measured operational output parameters included the thrust force F (kN), the rotation speed n (rpm), as well as the output characteristics of the drilling process – the penetration depth p (mm) and the torque T (Nm). The specific energy values were calculated from the individual experiments. A correlation between the specific energy and the wear intensity was analysed.

Theoretical background

A drilling process is based on rock destruction using a drilling tool and removing disintegrated chips from the drill hole bottom. Rock disintegrates due to the combined effects of pressure and rotation of the drill bit. The drill bit plays a key role in transferring energy from the drilling equipment to the rock and during the rock disintegration. During the drilling, the material is constantly removed from the rock surface due to the friction between the drill bit–and rock contact surfaces. In an ideal situation, the process in which an impregnated diamond drill bit wears consists of three consecutive stages. Active diamonds initially wear due to their contact with the rock (the polishing process). Subsequently, the worn diamonds are released from the matrix. Eventually, the matrix fully wears, and new diamonds appear (the self-sharpening mechanism). Interruption of the diamond replacement process may change the balance between the diamond wear rate and the matrix; as a result, the drilling process cannot be conducted in optimal conditions. The wear causes the quality of the working surface of the drilling tool deteriorates, and hence its functionality and service life impair (Huang & Wang, 1997).

Wear is significantly affected by the selected drilling mode, the amount of energy transferred from the drilling tool to the rock, the force conditions in the zone of contact between the drilling tool and the rock, and the properties of the drilled rock. The wear intensity I_o (mm.m^{-1}) was defined as a ratio of the loss of the drill bit matrix height Δh (mm) per 1 m of the drilled length l (m)

$$I_0 = \frac{\Delta h}{l} \quad (mm.m^{-1})\,. \tag{1}$$

The correlation between the diamond drill bit wear and the mechanical rock breaking is most significantly manifested in the amount of energy consumed by drilling. The energy consumption of the drilling process is identified using the values of specific energy SE (MJ.m^{-3}), which was introduced into the drilling research by Teale (Teale, 1965). It expresses the amount of energy necessary to break a unit volume of rock. Continuous theoretical and experimental research into mechanical rock breaking has brought new knowledge to define the equations for calculating specific energy (Meng et al., 2012; Zhou et al., 2017; Deng et al., 2022). Equation 2, a mathematical expression of specific energy,

$$SE(F) = \frac{2\pi\, T(F)}{A.\, p(F)} \quad (MJ.m^{-3}) \tag{2}$$

clearly shows that the variable parameter in that equation is $\frac{T(F)}{p(F)}$, wherein T (Nm) is the torque and p (mm) is the penetration depth as a function of the thrust force F (N). In the equation, A (m^2) is a constant expressing the surface area of the contact between the tool and the rock.
The correlation between the torque T (Nm) and the thrust force at a quasi-constant rotation speed is described by the derived Eq. 3, which represents, for an astatic system (Dorčák et al., 2006), the solution of a second-order differential equation with constant coefficients:

$$T(F) = \kappa\left[F + \Theta\left(e^{-\frac{F}{\Theta}} - 1\right)\right] \quad (N.m) \tag{3}$$

wherein F (N) is the applied thrust force. The substitution coefficient κ (mm) expresses a linear response of the torque to the growing thrust force; and θ (N) represents a delay in the response of the drilling set at low thrust force values.
The mathematical expression of curve p (mm) as a function of the thrust force F (N) is the solution of the second-order differential equation with constant coefficients (Krúpa et al., 2018):

$$p(F) = p_{max}[1 - e^{-\omega.F}(1 + \omega.F)] \quad (mm) \tag{4}$$

wherein F (N) is the applied thrust force, p_{max} (mm) is the maximum penetration depth to which the equation solution converges, and ω (N^{-1}) is the substitution coefficient.
Substitution coefficients κ (mm), **Θ (N)**, p_{max} (mm), and ω (N^{-1}) were calculated in the Matlab software environment using the algorithm based on the method of least squares. The experimentally measured values were compared to the theoretical values calculated from the derived mathematical models of Eq. 3 and Eq. 4. The result of the solution of the theoretical models of penetration depth and torque was a combination of substitution coefficients, for which the sum of the squares of differences between the experimental and the theoretical values was minimal.
After the substitution of Eq. 3 and Eq. 4 to Eq. 2, the mathematical model of specific energy was as follows:

$$SE(F) = \frac{2\pi}{A}\, \frac{\kappa\left[F + \Theta\left(e^{-\frac{F}{\Theta}} - 1\right)\right]}{p_{max}\,[1 - e^{-\omega F}\,(1 + \omega F)]} \quad (MJ.m^{-3})\,. \tag{5}$$

The basic prerequisite for achieving cost-effective drilling is to reduce the amount of energy required for rock breaking in particular geological and geotechnical conditions; that may be achieved, for example, by determining the zone of thrust forces using a mathematical model, where specific energy reaches its minimal values. The first derivation of specific energy relative to thrust force, equal to zero, facilitated the identification of the value of optimal thrust force – F_{opt}, which is the argument of the minimum specific energy – SE_{min}. It is calculated using Eq. 6:

$$[1 - e^{-\omega F}(1 + \omega F)]\left(1 - e^{-\frac{F}{\Theta}}\right) - \left[F + \Theta\left(e^{-\frac{F}{\Theta}} - 1\right)\right]\omega^2 F e^{-\omega F} = 0 \tag{6}$$

wherein Θ is the coefficient calculated from Eq. 3, and ω is the coefficient calculated from Eq. 4.

Results and discussion

Laboratory tests were performed to understand how impregnated diamond drill bits wear during the drilling into selected rocks and examine the correlation between the wear intensity and the energy consumption of the drilling process.

In each measurement series, which included drilling with an increasing thrust force and a rotation speed of $n = 500$; 1,000; 1,500; and 2,000 rpm, average values of specific energy $\overline{SE}$ were calculated for each rock–drill bit pair, as shown in Fig. 3.

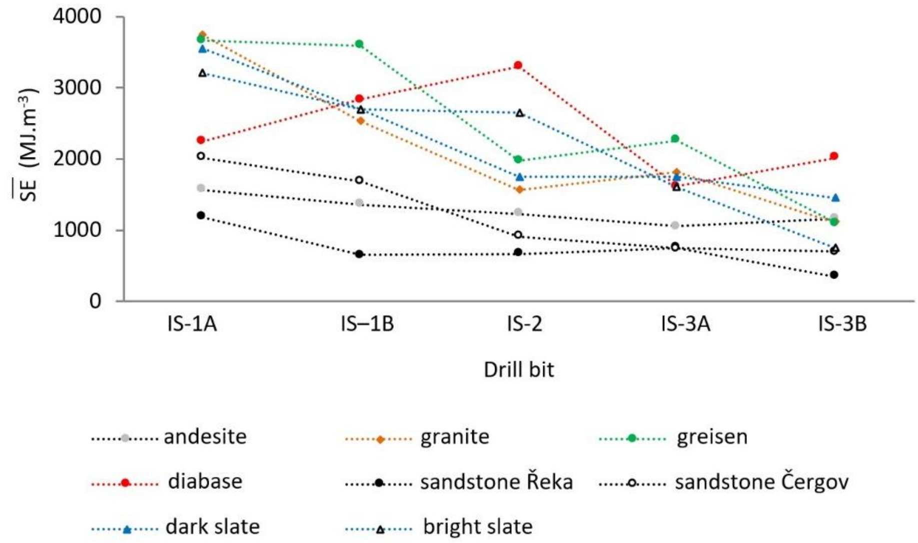

Fig. 3. Average values of specific energy calculated for each rock–drill bit pair

The plot values clearly show that drilling into sandstone and andesite required the lowest amount of energy. That is determined by the destruction mechanism. The destruction of rock under the diamond embedded in the drill bit matrix was comparable to the destruction under the indenter during the measurement of rock strength. Research into the destruction mechanism during the measurement of uniaxial compressive strength of tested rocks on the test press in the laboratory of the Institute of Geotechnics of the Slovak Academy of Sciences revealed that significant radial cracks were typically formed on the edge of crushed zones of andesite and sandstone samples after a crater was chipped off. As for the remaining types of rock, the formation of a crater was mainly observed. Based on the aforesaid observations, it may be concluded that the formation of radial cracks significantly improves the drilling energy balance.

Tab. 3 shows the rotation speed values (rpm) for 5 impregnated drilling tools and 8 different rock types, for which the minimal values of specific energy were identified.

Tab. 3. Rotation speed (rpm) with a minimal value of specific energy for impregnated diamond drill bits

Drill bit	Rock							
	Andesite	Granite	Greisen	Diabase	Sandstone Řeka	Sandstone Čergov	Dark slate	Bright slate
IS-1A	2,000	2,000	2,000	2,000	2,000	2,000	2,000	1,500
IS-1B	2,000	2,000	2,000	2,000	500	1,500	2,000	1,500
IS-2	2,000	1,500	500	1,500	2,000	2,000	1,000	2,000
IS-3A	1,500	1,000	1,000	2,000	1,000	2,000	2,000	1,000
IS-3B	2,000	2,000	2,000	1,500	2,000	1,500	2,000	1,500

Based on the evaluation of the calculated data, it may be stated that during the drilling with the use of impregnated diamond drill bits, the lowest values of specific energy with approximately 80% confidence were observed at the rotation speeds of 1,500 and 2,000 rpm.

After each experiment, the degree of wear of the tested drill bit was examined by measuring the loss of the matrix height. Tab. 4 shows the values of the drilled length (m) by the drill bit in the given rock and the measured loss of the drill bit matrix height Δh (mm).

Tab. 4. Measured values of the drilled length l(m) and the loss of the matrix height Δh (mm) for the tested rocks and drill bits

		Drill bit				
		IS-1A	IS-1B	IS-2	IS-3A	IS-3B
Diabase	l [m]	0.68	0.3	0.818	0.46	0.51
	Δh [mm]	0.44	0.1	0.2	0.11	0.1
Sandstone Čergov	l [m]	0.515	0.855	0.829	0.55	0.962
	Δh [mm]	1.03	0.9	0.38	0.05	0.02
Andesite	l [m]	0.59	0.515	0.785	0.48	0.928
	Δh [mm]	0.55	0.6	0.1	0.05	0.1
Sandstone Řeka	l [m]	0.97	1.035	0.978	0.645	0.796
	Δh [mm]	1.4	2.2	1.05	0.15	0.4
Greisen	l [m]	0.86	0.86	0.73	0.525	0.975
	Δh [mm]	1.45	0.9	1.05	0.6	0.2
Granite	l [m]	0.605	0.89	0.77	0.77	0.914
	Δh [mm]	1.79	1.3	0.35	0.47	0.23
Dark slate	l [m]	1.07	1.4	1.055	0.665	0.967
	Δh [mm]	0.9	0.5	0.2	0.08	0.05
Bright slate	l [m]	0.6	0.82	1.12	0.845	1.2
	Δh [mm]	0.45	0.39	0.3	0.35	0.1

Equation 1 was used to calculate the wear intensity. Fig. 4 shows the curves of the correlation between the wear intensity I_o (mm.m^{-1}) and the average values of specific energy $\overline{SE}$ (MJ.m^{-3}) by rocks. The plotted variables were found to exhibit a direct linear correlation (Meloun & Militký, 2004).

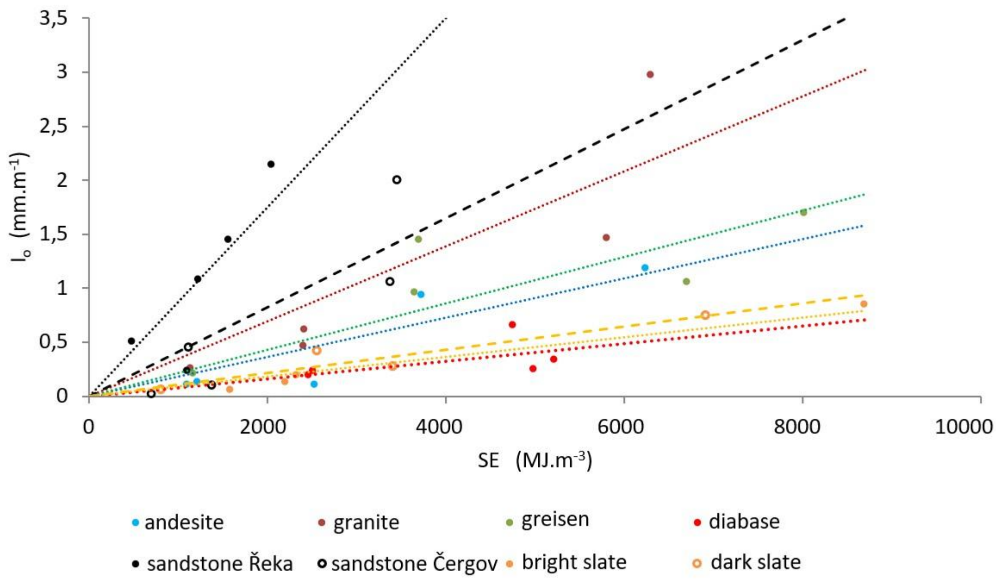

Fig. 4. Correlation between the wear intensity and the average values of specific energy by rocks

Different structural properties, strengths, and deformation characteristics of the drilled rocks affected the intensity of wear of the drill bits and the energy consumption of the drilling process. The lowest values of the wear intensity at high values of specific energy were observed for magmatic rocks. The highest wear intensity was observed for sedimentary rocks at a relatively low energy consumption during the drilling process.

Regression and correlation coefficients (Hendl, 2004) identified for the individual types of rocks are listed in Tab. 5.

Tab. 5. Values of the regression coefficient (R) and the correlation coefficient (R^2) of linear regression lines for the tested rocks

	Andesite	Granite	Greisen	Diabase	Sandstone Řeka	Sandstone Čergov	Dark slate	Bright slate
R	0.1821	0.347	0.2153	0.0812	0.8757	0.4122	0.0914	0.108
R^2	0.8049	0.7719	0.5379	0.4441	0.7116	0.7253	0.9535	0.8852

The lowest regression coefficient was observed for diabase but at a low correlation coefficient.

Fig. 5 shows the correlations between the wear intensity and the average values of specific energy by drill bits.

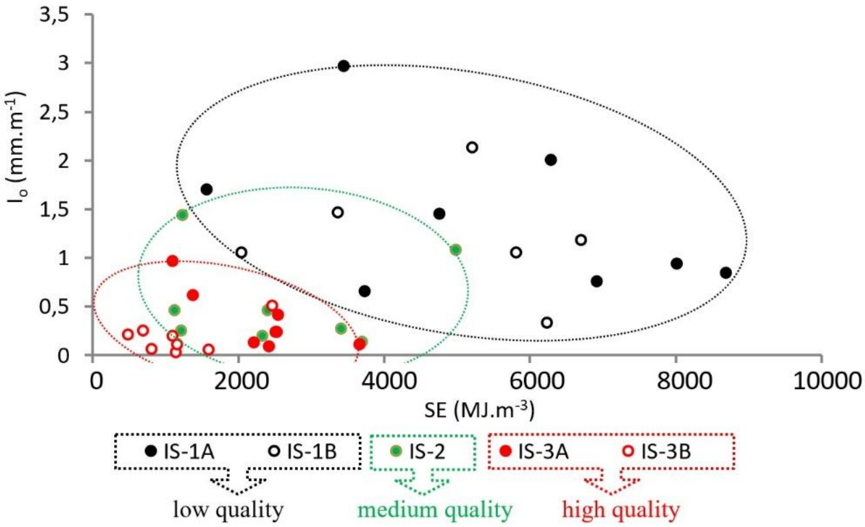

Fig. 5. Correlations between the wear intensity and the average values of specific energy by drill bits and quality of embedded diamonds

During a drilling process, the diamonds that are in contact with the rock are subjected to high pressures and impacts that lead to the wear of the diamonds. Due to the fact that the prevailing mechanism of how synthetic diamond grains wear away during the drilling is brittle fracturing of the protruding parts of the grains, the tool performance rate largely depends on the quality of grains (Miller & Ball, 1991). The aforesaid fact was also confirmed in the experiments conducted in the present research, as shown in Fig. 4. The comparison of drill bits in terms of the intensity of their wear clearly showed that the wear intensity decreased as the quality of diamonds increased, while the distribution of specific energy values decreased.

Conclusions

In this article, the specific energy and the wear intensity of drill bits during the drilling were examined. Tests of rotary drilling were performed on eight types of rocks taken from different locations. The drilling was carried out using 5 impregnated diamond drill bits with embedded synthetic diamonds of different qualities. The conclusions made based on the experimental drilling are as follows:

- The lowest energy required for the drilling was observed for sandstone and andesite – the rocks in which radial cracks were formed around the chipped-off crater during the drilling;
- At selected values of rotation speed (500; 1,000; 1,500; and 2,000 rpm), the lowest values of specific energy with approximately 80% confidence were observed at the rotation speeds of 1,500 and 2,000 rpm;
- The correlation between the intensity of wear of the drill bits and the specific energy for the individual rock types was analysed based on a simple regression analysis. The identified linear regression may be used to predict the height loss caused by the wear of the drill bit matrix;
- The comparison of drill bits in terms of wear intensity showed that the wear intensity also depends on the quality of the used diamonds. The obtained results showed that as the quality of diamonds increased, the values of specific energy decreased and exhibited a lower distribution.

The results presented demonstrate that appropriately selected drill bits and drilling parameters facilitate minimising the energy efficiency of the drilling process and, hence, affect the overall effectiveness and cost of drilling.

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