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Planning experiment for laboratory tests on rock abrasivity

The physical and mechanical properties of rocks (i.e., compressive strength, tensile strength, workability, or compactness) are often taken into account during the selection of a mining method and type of mining machine as well as the mining tools themselves. However, one of the main reasons for the abrasive wear of mining picks is the abrasiveness of rocks, which is seldom taken into consideration because there is lack of unambiguous and proven methods for its determination.
The article presents the research plan and methodology, the stand for testing the abrasivity of rocks, the course of conducting preliminary tests as well as the statistical treatment of the results using the Statistica program, and determining the final values of the input variables in the basic research. The method has been developed taking into account rock abrasivity when selecting and forecasting the wear of mining tools.

Key words: *rock abrasivity, design of experiment, laboratory test method, statistical analysis, mining tools, abrasive wear*

1. INTRODUCTION

Knowledge of the physical and mechanical properties of rocks is of great importance in the design and implementation of all engineering projects in mining and underground construction. It is necessary to evaluate the stability of the rock mass in the vicinity of excavations and provide conditions for the safe use of the excavations and safe work [1]. Physical-mechanical parameters should also be considered as the basis for choosing the method of mechanical mining. This expertise allows us to evaluate the usefulness of rocks as well as assess the behavior of rocks during the mining process [2].

An element that is in direct contact with the mined rock during extraction work is the cutting pick. As a result of the mining process, the tools are subjected to excessive wear, most often by abrasion. Their wear can have very serious consequences, among which are changes in the geometrical shape of the pick, losses in its weight, a loss of its cutting capacity, frequent pick replacement, shortening the working time of the mining machine, reduced efficiency, and increased energy consumption and mining costs [3, 4].

When selecting mining tools, various aspects are taken into account among other geological properties as well as the physical and mechanical properties of the rocks, where the most commonly considered parameters are uniaxial compression strength, uniaxial tensile strength, compactness, and workability. It is also necessary to choose the right material and construction of the picks so that their durability is as great as possible with the parameters given as well as the cutting process conditions [3, 4].

When selecting mining tools, the abrasivity of rocks is very rarely taken into account. This is due to the lack of a clearly defined method of its determination. The only commonly known test method for identifying a rock's abrasivity is the Cerchar Abrasivity Index (CAI) [5, 6]. This test is used by the Sandvik company; however, the test results are a company secret. Often, the rock abrasivity testing methods are confused with rock abrasiveness testing methods, as described in publication [3].

In connection with all of the above, a new rock abrasivity test method has been developed (which is described in this article).

2. LABORATORY TEST STAND

The abrasivity of rocks is determined using abrasivity index W_z. The formula of its determination is based on the evaluation of the durability of the cutting picks. Under industrial conditions, the durability of cutting picks is usually defined as the ratio of the number of replaced picks to the weight or volume of the extracted material. Most frequently, it is the number of worn picks necessary to obtain 1000 Mg or 1000 m^3 of extracted material. However, under laboratory conditions, the wear rate (durability) of picks is most effectively determined on the basis of the loss of their weight in relation to the volume of the rock specimen extracted [4]. On this basis, the abrasivity index is defined as the ratio of the loss weight of the model steel pin to the weight loss of the tested rock sample (1).

$$W_z = \frac{M_{pa}}{M_{pi}} \tag{1}$$

where:
- W_z – abrasivity index [–],
- M_{pi} – weight loss of the rock sample [g],
- M_{pa} – weight loss of the steel pin [g],

$$M_{pa} = M_{pab} - M_{paa} \tag{2}$$

where:
- M_{pab} – steel pin weight before test [g],
- M_{paa} – steel pin weight after test [g],

$$M_{pi} = M_{pib} - M_{pia} \tag{3}$$

where:
- M_{pib} – rock sample weight before test [g],
- M_{pia} – rock sample weight after test [g].

The method of determining the abrasivity index has forced the design and construction of a laboratory test stand (Fig. 1). The test stand has a drive unit that carries out rotational movement of the steel pin at a constant speed. On the shaft of the gearmotor, there is a holder in which a steel pin is fixed. Together with the rock sample, they form an abrasive pair (Fig. 2). The steel pin is constantly pressed against the face of the rock sample by means of a gravitational holding-down system with the weights. A detailed description of the test stand has been presented in publication [7].

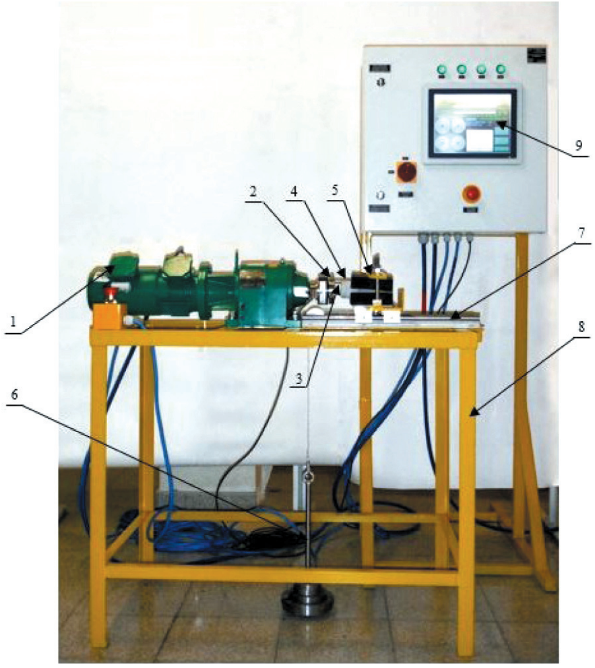

Fig. 1. Test stand for determining rock abrasivity: 1 – drive unit, 2 – steel pin, 3 – holder of steel pin, 4 – rock sample, 5 – holder of rock sample, 6 – gravitational holding-down system, 7 – sliding system, 8 – supporting frame, 9 – control panel

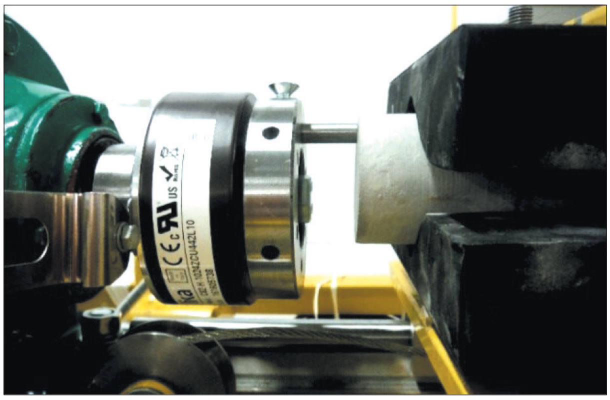

Fig. 2. View of abrasive pair

3. PURPOSE AND CHARACTERISTIC OF RESEARCH OBJECT

The first important step in the research is to raise a research problem that requires a solution through experimentation and a description of the research object. The goal of each type of experimental research is to obtain information on the relationship between the input (set parameters) and output variables (wanted parameters). This type of relationship is usually represented as an approximating function of a research object [8, 9].

Characteristics of the research object lie in determining a set of input and output variables. This stage of research is of key importance, as the errors connected with the inaccurate recognition of the research object may result in obtaining a lack-of-fit model as well as a loss of money and time. It is therefore important to become familiar with the topic, which is described in article [3].

In the preliminary research described in this article, the main goal was to determine the form of the functions for three different rock samples and then calculate the values of the input variables that stay unchanged in the basic research. Abrasivity index W_z is an output variable, whereas the input variables are as follows:

- feed force of the steel pin to the rock sample P_d [N],
- rotational speed of the steel pin n [rpm],
- time of single test t [min].

The subject of the research are two types of natural rocks (sandstone and porphyry) as well as concrete (shown in Fig. 3).

Fig. 3. View of prepared samples for tests: 1 – sandstone, 2 – concrete, 3 – porphyry

The selection of such a set of samples was conditioned by different physico-mechanical properties and diversified mineralogical and chemical composition. Particular attention is paid to the value of uniaxial compression strength. Sandstone is a rock with high strength and has good abrasive properties due to its high silica (SiO_2) content. Porphyry is a rock with medium strength and also has good abrasive properties due to its silica (SiO_2) content. On the other hand, C16/20 concrete was selected for artificial samples to obtain samples with low compressive strength and additionally basalt aggregate was added in order to check whether the inclusions would chip or not.

Table 1

Uniaxial compressive strength and percentage content of silica (SiO_2) in tested samples

Sample	Uniaxial compressive strength R_c [MPa]	Content of silica SiO_2 [%]
Sandstone	100–110	27.7
Porphyry	32–53	21.9
Concrete	20–25	15.2

4. SELECTION OF DESIGN OF EXPERIMENT

In order to reduce the workload and time consumption, the scope of the research is most often narrowed by eliminating input variables or reducing the number of input variables [8]. The best solution is to apply the proper design of the experiment. One of its greatest advantages is the ability to obtain measurable effects by reducing the work needed to conduct an experiment; it also reduces time consumption. However, the choice of the design of the experiment depends on the purpose and specificity of the type of research. Using the theory of the experiment, one should choose a design of an experiment that meets the basic criteria of informativity, realizability, and efficiency [8–10].

As mentioned before, there are three input variables and one output variable in the case of the described research. Assuming nonlinear functional relationships between the input and output variables, a test is carried out for five intermediate values. It is assumed that, for the first variable (which is the P_d feed force), the variation range is 150–350 N. For the second variable, the rotational speed of steel pin n varies between 20–55 rpm, and for the third (time of single test t), the range is 4–12 min.

Due to the high efficiency, the ability to describe nonlinear models of the research object and at the same time the compositionality (that is, the ability to verify the linear model), *Hartley's test (PS/DS-P:Ha$_3$)* based on a hypersphere has been selected. It is a test that belongs to the static determined and polyselective tests for three input variables in which five different values are used for each input variable [9].

The basic principle of creating polyselective tests is the deliberate selection of a combination of input variables (in the previously assumed range) in such a way that it is possible to obtain the required scientific information with a limited workload; that is, with a relatively small number of measurements [9, 10]. The Statistica program is very helpful at this stage of the research. It enables the generation of various types of design of experiments thanks to the *Design & Analysis of Experiments Startup Panel* [11].

The choice of a polyselective test significantly reduces the number of necessary single tests as related to the full factorial design. As be seen in Table 2, the combinations of values of input variables from Numbers 11 through 14 show the same combination of input variables. Repetition of the experiment for these combinations is necessary to determine the errors of the assumed approximating function of a research object.

Table 2

Combinations of values of input variables applied during preliminary research in Hartley's test

Hartley's test treatments	Feed speed P_d	Rotational speed n	Single test time t
1	192	27	10
2	308	27	6
3	192	48	6
4	308	48	10
5	150	37	8
6	350	37	8
7	250	20	8
8	250	55	8
9	250	37	4
10	250	37	12
11	250	37	8
12	250	37	8
13	250	37	8
14	250	37	8

Unfortunately, after doing the tests for the determined design of the experiment and carrying out the statistical analysis of the tests results, it is found that the designated functions of the research object for each tested sample are a lack-of-fit as related to the measurement results. Additional tests are carried out for several other designs of the experiments; however, each time too few measurements are obtained, thus attaining an inaccurate function describing the research object. In connection with all of the above, the need arises to use a full factorial design.

5. EXECUTION OF RESEARCH PLAN

The choice of a full factorial design is associated with a large amount of work and is excessively time-consuming. Due to the cognitive character of the research, the range of variability of the input variables is expanded for the full factorial design as related to the previously mentioned designs of the experiments. It has been decided to obtain a greater amount of data in order to determine a more precise approximating function of a research object. The ranges of variation and the values tested for the full factorial design are presented in Table 3. The input variables' values are chosen symmetrically for each range of the variations. Such a selection is necessary to accurately reflect the character of the variability of the input variables for the research result [9, 12].

Table 3

Ranges of variation and selected values of input variables

Input variables	Feed force P_d [N]	Rotational speed n [rpm]	Single test time t [min]
Ranges of variation	100–400	10–65	2–15
Selected values	100, 200, 300, 400	10, 30, 50, 65	2, 5, 10, 15

The combinations of the values of the input variables accepted for the individual tests are determined by the full factorial design. Having three input variables with four test values each means that 64 single tests (4 × 4 × 4) have to be carried out for each sample. For the three rocks, the total number of single tests is 192. Due to the large amount of data, individual treatments of the full factorial design are not included in this article.

The tests are carried out on a laboratory test stand for determining rock abrasivity (described in the second chapter) according to the following research plan:

- preparation of rock samples and measurement of their weight,
- preparation of steel pins for testing and measuring their weight,
- fixing the steel pin and rock sample in the holders on the test stand,
- setting the test time and rotational speed of the steel pin on the control panel,
- setting the feed force of the rock sample to the steel pin by means of a gravitational holding-down system with weights,
- carrying out the test,
- releasing the feed force,
- dismantling the steel pin and measuring its weight,
- dismantling the rock sample and measuring its weight,
- calculation of the weight loss of the steel pin and rock sample,
- determination of abrasivity index W_z.

In addition to the abrasivity index W_z values for each combination of input values, the carried-out tests enable us to obtain many other valuable conclusions, including the following:

- a test time of 2 minutes is too short, while a feed force of a steel pin to a rock sample of 100 N and a rotational speed of 10 rpm are both too small to obtain a measurable wear of a steel pin with the necessary accuracy of 0.01 grams,
- a rotational speed of a steel pin at 65 rpm and a feed force of 400 N (independent of the time of a single test) cause it to heat up, consequently leading up to the high-temperature sliding wear of a steel pin and even its melting.

Based on the above observations, the treatments with these input values and, thus, the values of abrasivity index W_z, are not taken into account in the analysis of the results.

6. ANALYSIS OF RESEARCH RESULTS AND SELECTION FUNCTIONS OF RESEARCH OBJECT

Having determined the abrasivity indices for all treatments of full factorial design, an analysis of the research results is performed to determine the functions of the research object for each sample.

Predetermined significance level p is 0.05 in all simulations; this is a value usually accepted in technical experimental studies [8–12].

The first step in the analysis of the results is to check if the variance is homogenous. This is a prerequisite condition. The lack of homogeneity of the variance enables a search for the functions of the research object. The homogeneity of variance is carried out with the Brown–Forsythe test with the Statistica program using the *Basic Statistics and Tables* module *(One-way ANOVA)*. If the test gives non-statistically significant results ($p = 0.05$), then the null hypothesis should be accepted [8]. As can be seen in Figure 4, significance level p is higher than 0.05 for all three tested rocks; hence, the variance is homogenous.

Before determining the functions of the research object, it is also checked whether the influence of the input variables on the output variable is significant or not. The verification is carried out with the F-test (Fisher's test) using the *Basic Statistics and Tables* module *(One-way ANOVA, Analysis of Variance)*. The obtained values of significance level p lower than 0.05 indicate a noteworthy influence of the input variables on the output variable.

The analysis of variance (Fig. 5) carried out using the F-test showed a significant effect of the feed force, rotational speed, and test time on the abrasivity index value for all three tested rock samples.

Brown-Forsythe test (Full factorial design)
Marked effects are significant at p < .05000

Variable	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Wz (sand)	1.120500	3	0.560250	3.580000	60	0.210588	2.660405	0.098806
Wz (con)	0.114500	3	0.057250	1.097500	60	0.064559	0.886788	0.430196
Wz (por)	0.009656	3	0.004828	0.033594	60	0.001976	2.443256	0.116766

Fig. 4. Results of Brown–Forsythe test for all three tested rocks

Variable	Analysis of variance (Full factorial design) Marked effects are significant at p < .05000							
	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Wz (sand)	29.06889	3	9.689629	77.74373	60	1.295729	7.478131	0.000247
Wz (con)	7.96197	3	2.653991	30.38804	60	0.506467	5.240201	0.002804
Wz (por)	8.84422	3	2.948073	28.13938	60	0.468990	6.286009	0.000882

Fig. 5. Results of F-test for all three tested rocks

When analyzing the results, the value of P_d is divided by 10 to minimize numeric errors. Next, the form of the function describing the empirical dependence (4) for each of the examined rocks is determined. A preliminary comparison of the degree of adequacy of the various forms of the approximation functions describing dependence (4) resulted in the selection of the form of the function as a second-degree polynomial with double interactions (5).

$$W_z = f(P_d, n, t) \tag{4}$$

$$\begin{aligned} z = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{11}x_1^2 + b_{22}x_2^2 + \\ + b_{33}x_3^2 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 \end{aligned} \tag{5}$$

The number of unknowns b_j of the proposed approximation polynomial is 10 and is smaller than the number of treatments of the full factorial design, which fulfills the necessary condition due to the criterion of informativity [7]. The b_j constants are calculated with the *quasi*-Newton estimation method using the Statistica program.

On the basis of an analysis of the coefficients of significance b_j carried out using the Student t-test, the rejected coefficients are considered non-significant (with a significance level of 0.05). The Advanced Linear/Nonlinear Models module (Nonlinear Estimation, User-Specified Regression) is used. The significance coefficients are marked in red (Fig. 6). Then, it is required to remove the components with non-significant coefficients from the polynomial and regenerate the new coefficients of the equation so that all of them are marked in red (all considered significant).

An example of the results for sandstone is presented in Figure 6. In the same way, the analysis of significance is also carried out for porphyry and concrete. The approximating functions for the three tested rocks are as follows:

– sandstone:

$$\begin{aligned} W_{z_1} &= -3.67 + 0.66 \cdot t + \\ &+ 0.2 \cdot P_d - 0.03 \cdot t^2 - 3 \cdot 10^{-3} \cdot P_d^2 \end{aligned} \tag{6}$$

– concrete:

$$\begin{aligned} W_{z_2} &= -2.45 + 0.3 \cdot t + \\ &+ 0.17 \cdot P_d - 0.014 \cdot t^2 - 3.3 \cdot 10^{-3} \cdot P_d^2 \end{aligned} \tag{7}$$

– porphyry:

$$\begin{aligned} W_{z_3} &= -6.8 \cdot 10^{-3} \cdot t^2 - 2.6 \cdot 10^{-4} \cdot n^2 - \\ &+ 7.2 \cdot 10^{-4} \cdot P_d^2 + 1.6 \cdot 10^{-3} \cdot t \cdot n + \\ &+ 4.3 \cdot 10^{-3} \cdot t \cdot P_d + 8.7 \cdot 10^{-4} \cdot n \cdot P_d \end{aligned} \tag{8}$$

where:

W_z – abrasivity index [–],
t – time of single test [min],
n – rotational speed of the steel pin [rpm],
P_d – feed force of the steel pin to the rock sample [N].

	Model: v5=b0+(b1*v2)+(b2*v3)+(b3*v4)+(b11*v2^2)+b22*v3^2)+(b33*v4^2)+(b12*v2*v3)+(b13*v2*v3)+(b13*v2*v4)+(b23*v3*v4) (Full factorial design) Inp. var. Wz (sand) Significance level: 95.0% (alpha = 0.050)					
	Coefficient	Standard Error	T Value df = 54	p	Low Confidence	High Confidence
b0	-3.77469	1.118300	-3.37538	0.001372	-6.01675	-1.53263
b1	0.55707	0.132698	4.19807	0.000101	0.29103	0.82312
b2	0.03936	0.031201	1.26143	0.212577	-0.02320	0.10191
b3	0.16433	0.064326	2.55465	0.013482	0.03536	0.29329
b11	-0.02925	0.006507	-4.49572	0.000037	-0.04230	-0.01621
b22	-0.00052	0.000355	-1.46293	0.149282	-0.00123	0.00019
b33	-0.00310	0.001132	-2.67230	0.009939	-0.00543	-0.0078
b12	-0.00113	0.001132	-1.00215	0.320743	-0.00340	0.00113
b13	0.00206	0.002098	0.98403	0.329489	-0.00214	0.00627
b23	0.00071	0.00501	1.40964	0.164380	-0.00030	0.00171

	Model: v5=b0+(b1*v2)+(b3*v4)+(b11*v2^2)+(b33*v4^2) (Full factorial design) Inp. var. Wz (sand) Significance level: 95.0% (alpha = 0.050)					
	Coefficient	Standard Error	T Value df = 54	p	Low Confidence	High Confidence
b0	-3.66638	0.766369	-4.78409	0.000012	-5.19988	-2.13288
b1	0.56475	0.117299	4.81459	0.000011	0.33003	0.79946
b3	0.20822	0.060836	3.42258	0.001133	0.08648	0.32995
b11	-0.02925	0.006711	-4.35876	0.000053	-0.04268	-0.01582
b33	-0.00310	0.001196	-2.59089	0.012044	-0.00550	-0.00071

Fig. 6. Elimination of non-significant coefficients in Statistica program on example of sandstone test results

After removing the non-significant coefficients in each designated function, the adequacy of the research object function for the test results is checked. The adequacy is verified with the use of the $\chi 2$ (chi--square) test. The achieved significance level p is 0.120 (average value); it is greater than 0.05, which proves that the obtained functions are adequate in relation to the test results. In addition, correlation ratio R for the designated functions are also checked. For sandstone, this is $R = 0.92$; for porphyry – $R = 0.90$; and for concrete – $R = 0.81$ (Fig. 7).

Variable	R	R Square	Adjusted R Square
Wz (sand)	0.918444	0.843539	0.765309
Wz (con)	0.907918	0.824316	0.736473
Wz (por)	0.808076	0.652987	0.479480

Fig. 7. Correlation ratios for designated functions

Then, from Equations (6), (7), and (8), simultaneous equations (9) are arranged and solved using the MATLAB program in order to obtain the final values of the input variables P_d, n, and t. Each equation is compared to the maximum value of abrasivity index W_z, which is obtained during the tests in order to determine the minimum values of the input variables at which the steel pin has the greatest wear.

$$\begin{cases} -3.67 + 0.66 \cdot t + 0.2 \cdot P_d - 0.03 \cdot t^2 - 3 \cdot 10^{-3} \cdot P_d^2 = 3.0 \\ -2.45 + 0.3 \cdot t + 0.17 \cdot P_d - 0.014 \cdot t^2 - 3.3 \cdot 10^{-3} \cdot P_d^2 = 1.4 \\ -6.8 \cdot 10^{-3} \cdot t^2 - 2.6 \cdot 10^{-4} \cdot n^2 - 7.2 \cdot 10^{-4} \cdot P_d^2 + 1.6 \cdot 10^{-3} \cdot t \cdot n + \\ \quad + 4.3 \cdot 10^{-3} \cdot t \cdot P_d + 8.7 \cdot 10^{-4} \cdot n \cdot P_d = 1.7 \end{cases} \tag{9}$$

After solving the above simultaneous equations, the following values of the input variables are obtained: test time $t = 7.88$ min; rotational speed $n = 50.37$ rpm; and feed force of the steel pin to the rock sample $P_d = 30.48$ N.

As previously mentioned, the P_d force value is divided by 10 to reduce numerical errors. Therefore, the next step is to carry out check tests for the three tested rocks with the following values of input variables: $t = 8$ min, $n = 50$ rpm, and $P_d = 300$ N.

Then, tests are carried out for the designated input variables for the three tested rocks. Five replicates are made for each rock to check the repeatability of the results; these results are summarized in Table 4. In addition to each of the determined equations, the calculated input variables are substituted and obtained:

for sandstone:

$$\begin{aligned} W_{z_1} &= -3.67 + 0.66 \cdot 8 + 0.2 \cdot 35 - \\ &+ 0.03 \cdot 8^2 - 3 \cdot 10^{-3} \cdot 35^2 = 3.0 \end{aligned} \tag{10}$$

for concrete:

$$\begin{aligned} W_{z_2} &= -2.45 + 0.3 \cdot 8 + 0.17 \cdot 35 - \\ &+ 0.014 \cdot 8^2 - 3.3 \cdot 10^{-3} \cdot 35^2 = 1.0 \end{aligned} \tag{11}$$

for porphyry:

$$\begin{aligned} W_{z_3} &= -6.8 \cdot 10^{-3} \cdot 8^2 - 2.6 \cdot 10^{-4} \cdot 50^2 - \\ &+ 7.2 \cdot 10^{-4} \cdot 35^2 + 1.6 \cdot 10^{-3} \cdot 8 \cdot 50 \\ &+ 4.3 \cdot 10^{-3} \cdot 8 \cdot 35 + 8.7 \cdot 10^{-4} \cdot 50 \cdot 35 = 1.4 \end{aligned} \tag{12}$$

While analyzing the values of abrasivity index W_z from Table 4, it can be seen that the test results are almost identical to those obtained from the equations. This means that the selected approximating functions have been well-fitted, describing the object of research thoroughly.

As previously mentioned, the steel pin melts in several single tests. A too-high temperature of the steel pin may change the material properties of the steel and lead to thermal wear. Due to this, the temperature of the steel pin for each single test from Table 4 is checked by the thermal imaging camera for the determined values of the input variables.

Table 4

Comparison of test results for three rocks for designated input variables

No.	P_d [N]	n [rpm]	t [min]	W_z (sandstone)	W_z (concrete)	W_z (porphyry)
1	350	50	8	3.2	1.0	1.4
2				3.0	1.1	1.3
3				3.0	1.1	1.3
4				3.1	1.0	1.3
5				2.9	1.1	1.4
Average value from test				3.1	1.1	1.3
Value form equations				3.0	1.0	1.4

As shown in Figure 8, the maximum temperature of the steel pin fluctuates between 55–70°C regardless of rock sample type. Such a temperature neither makes the steel pin heat up too much nor shows a greater influence of heating wear on the abrasive wear [13, 14].

a) b) c)

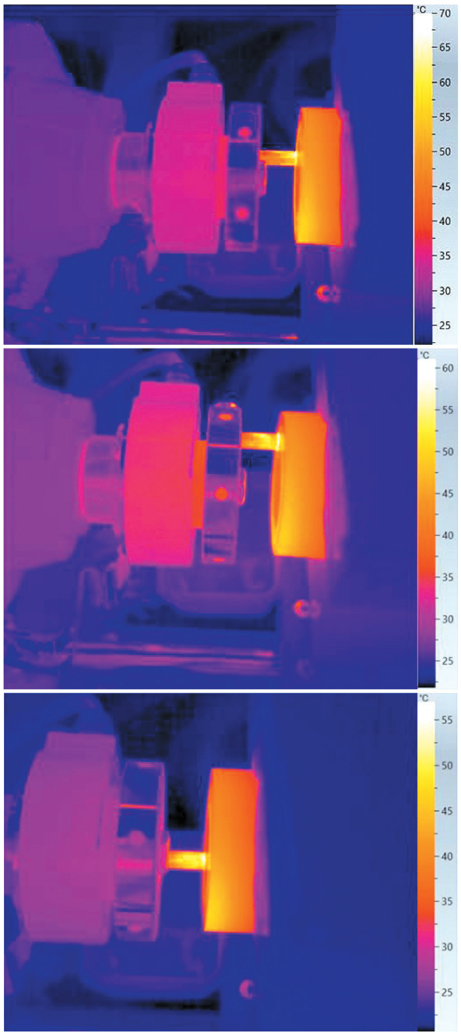

Fig. 8. Thermographic images of maximum temperature pattern during tests: a) sandstone; b) porphyry; c) concrete

7. SUMMARY

Carrying out preliminary research and statistical analysis of the results allowed us to verify the assumptions and make corrections in the research plan and methodology. The choice of a full factorial design allowed us to maintain a satisfactory accuracy in the determination of the approximating function of the interrelations between the input variables and the output variable. The most important goal was to determine the final values of the input variables: a feed force of the steel pin to the rock sample equal to 300 N, a rotational speed of steel pin equal to 50 rpm, and a test time of 8 minutes.

The next step will be to carry out basic research for different types of rocks. These will include limestone, dolomite, granite, marble, metal ores, various types of sandstone, and basalt (among others).

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