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IMPACT OF PHYSICAL AND MECHANICAL PROPERTIES OF ROCKS ON ENERGY CONSUMPTION OF JAW CRUSHER

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Abstract: The aim of this paper was to determine the impact of physical and mechanical properties of rocks on the electricity consumption of a jaw crusher during crushing. This paper presents a different approach to determine the energy consumption during comminution. The energy required for crushing rocks was obtained by direct measurement of crusher's motor power during the crushing of samples. Laboratory tests were used to determine the following physical and mechanical properties of the tested samples: bulk density, compressive strength, tensile strength, hardness, and fracture toughness. After that, the laboratory jaw crusher crushing tests were conducted. In the first part of the study, the individual rock samples were crushed one by one. In the second part of the test, multiple samples were crushed simultaneously. By measuring the energy consumption for crushing rocks with different physical and mechanical properties, we explored the dependence of energy required for crushing on individual mechanical properties of rocks and the simultaneous effect of the properties. Using statistical analysis of the influence of individual mechanical properties we found that the greatest influence on energy consumption for crushing was compressive strength. Fracture toughness and tensile strength of the rocks had a significant impact on the crushing energy. The effect of bulk density was not large while for the hardness could not be stated that it had influence. By the analysis of deviations of specific crushing energy calculated using equations obtained by multiple regression analysis of simultaneous influence of multiple mechanical properties of rocks and from the measured values, it was found that the dependence obtained on the basis of all investigated properties showed the smallest deviation and dependence obtained by compressive strength, fracture toughness, and hardness showed significantly smaller deviation. By examining the influence of mechanical rock properties on particle size of crushed material it was found that the increase in compressive strength increased the proportion of larger particles while other properties showed no effect.

Keywords: *mining, crushing, physical and mechanical properties of rocks, energy, crushed stone, jaw crusher*

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Introduction

Comminution is a process in which larger pieces of ore or rock form smaller pieces under exposure of mechanical forces, i.e. there is a change in dispersed state of solids which is uniquely determined by grain size composition. There are many reasons for using comminution: achieving the release of useful minerals from useless minerals as preparation for concentration, attaining certain size and shape of grain in producing concrete and asphalt, increasing the grain surface and thus its reactivity, changing structural and chemical characteristics i.e. mechanical activation (Salopek and Bedekovic 2000). All these make grinding an integral part of almost every process in mineral processing, and its importance and significance arise from the fact that it is highly energy demanding and also very inefficient and as such will always be an interesting area to explore. According to (Sadrai et al. 2011), "the energy efficiency of comminution equipment can be defined as the ratio of surface energy change to the mechanical energy input". According to this, grinding efficiency varies between 0.1% and 1% (Furstenau and Abouzeid 2002). Crushing efficiency is slightly higher beween 2% and 3% (Sadrai et al. 2011). According to Rittinger (1867) the energy required for comminution is proportional to the newly created (free) surface area. According to Kick (1885) the specific energy consumption during grinding is proportional to reduction in the diameter of the observed particles. According to Bond (1952) the energy is inversely proportional to the square root of the newly created surface area, which is a sort of compromise between "Rittinger's area" and "Kick's diameter." Kick's "law" gives good results for crushing, Bond's for grinding and Rittinger's for fine grinding.

Based on a large number of tests, Bond introduced a working index or comminution parameter that represents the resistance of the material to crushing and grinding. Characterization of rocks for selection of crusher can be done in different ways, and the most commonly used is Bond work index (Tavares and Carvalho 2007).

Holmes (1957) proposed a modification of Bond's equation with the additional coefficient that depends on the properties of rock.

There are several methods for the determination of resistance to crushing, however, two most commonly used methods are pendulum and falling weight tests. For the determination of the resistance to crushing, Bond's index is determined based on the average comminution energy for individual samples using a device with a double pendulum (Donovan 2003). Numerous authors have conducted tests of resistance to crushing by considering physical and mechanical properties.

Bearman (1991) conducted an extensive research on the impact of physical and mechanical properties of rocks on the performance of crushers. Based on these studies, the most important characteristics that affect crushing energy are fracture toughness, tensile strength, and point load index.

On the basis of the falling pendulum tests, Narayanan and Whiten (1988) developed a straightforward *t10* parameter that describes the distribution of classes in the grain-size composition of the crushed material. This parameter represents the proportion of fragmented particles smaller than 1/10 of the input grain sizes. The tests established the link between the specific comminution energy and the parameter *t10* (Napier–Munn et al. 1996).

Donovann (2003) analyzed the influence of individual characteristics on the performance of jaw crusher, and found that of all of the surveyed properties fracture toughness had a greatest impact on crushing energy.

Kujundzic et al. (2008) found that the energy required for crushing igneous rocks was higher compared to the crushing of sedimentary rocks. It was also found that the hardness showed no significant influence on the crushing energy. Olaleye (2010) found that the increasing uniaxial compressive strength increased the time required for crushing. Toraman et al. (2010) conducted tests on laboratory jaw crusher and found a link between the crushing index and the impact strength index.

Tosun and Konak (2014) developed a model to predict the energy consumption of primary and secondary crushers. According to this model, the specific energy of crushing depends on the specific consumption of explosives and uniaxial compressive strength. From an energy consumption viewpoint, it is clear that blasting with the intention of decreasing the Bond work index (*Wi*) will produce large energy savings (Workman and Eloranta 2003).

In the previous research the specific crushing energy was determined indirectly based on the pendulum or falling weight tests. None of these ways of testing simulates the motion of the jaw crusher's jaw. In this study, the effect of certain mechanical properties of rocks on crushing energy of jaw crusher was determined using direct measurement of the power on the jaw crusher motor.

Materials and methods

For the purposes of laboratory tests we collected samples of igneous and sedimentary rocks of different physical and mechanical characteristics from seven surface mines of crushed stone: Ivanec, Belaj, Spica, Kremesnica, Jelenje vode, Brensberg, and Zervanjska. All quarries are located in Croatia: “Ivanec” and “Jelenje vode”near Zagreb, “Belaj” near Karlovac, “Špica” near Ljubeščica, “Kremešnica” near Lasinja, “Brensberg” and “Žervanjska” near Orahovica. The sampling was carried out in such a way that the pieces of rocks had any visible cracks selected from the blasted rock mass. The previous studies have showed that the energy requirements for comminution depend on the size of the material and its distribution (Stamboliadis 2002), and that "shape of rocks and its contacts with the jaws may have considerable effect on the comminution energy" (Refahi et al. 2007). Therefore, in the laboratory from the larger pieces of rock by coring samples for crushing were obtained, then the determination of the physical and mechanical properties was performed in accordance with the methods recommended by ISRM. Thus, the laboratory testing consisted of two parts: the determination of physical and mechanical properties of samples and measuring electricity consumption during the crushing.

According to the test methods proposed by ISRM the following properties were determined: bulk density, tensile strength, hardness, and fracture toughness. Compressive strength tests were conducted on the samples in the form of a cube with the length of each side d=5cm. It is known that the value obtained in such a way is higher than in the testing of samples according to the recommendations of ISRM. Therefore, the values were calculated using the empirical relation (Eq. 1) proposed in ASTM:

$$\sigma_{c1} = \frac{\sigma_c}{0.788 + \frac{0.222}{\left(\frac{h}{d}\right)}} \tag{1}$$

where:

σ_{c1} compressive strength of samples with ratio $h/d = 1$

σ_c compressive strength of samples with ratio $h/d > 1$

d diameter of samples that are in the form of a core or length of edge if samples are in the form of a cube

h height of the sample.

Calculated values of compressive strength were obtained with the ratio h/d=2.5. The second part of the tests included the measurement of the specific crushing energy in a laboratory jaw crusher Loro & Parisini. The feed size of the opening was 250 mm × 190 mm, and the granulation aperture size could be controlled in the range of 35 mm to 65 mm. During the tests, the opening was set to a minimum value of 35 mm. The technical characteristics of the other jaw crusher are presented in Table 1.

Table 1. Technical characteristics of the laboratory jaw crusher Loro & Parisini

Nominal voltage	380 V
Nominal power	5.5 kW
Nominal current	11.7 A
Frequency	50 Hz
$\cos\Phi$	0.84
Engine speed	1440 min^{-1}
Jaw speed	280 min^{-1}

The measurement of the specific crushing energy was conducted in two phases. In the first phase five individual samples from each quarry were crushed, and in the second phase in each individual test three samples were simultaneously crushed. The crushing tests were conducted in two phases in order to determine whether the specific energy depends on the quantity of the material being crushed.

Due to the fact that the average time for crushing one sample was about 3 s, the measurement system was designed (Fig. 1), which enabled the recording of data on the current power used by the electric engine that drives the jaw crusher at the rate of 20 readings per second. On the diagram of the time-power dependence, energy is represented by the area under the power curve. The energy required for the crushing of individual samples was obtained indirectly, by measuring electrical power. For this purpose, the measuring transducer MI 400 with a measuring range of voltage up to 500 V and currents up to 5 A, which was set to measure apparent, active and reactive power was converted to DC voltage in the range of ± 10 V on three separate analog outputs. The output voltage is proportional to the power consumed by the motor. Mains voltage was about 400 V, and the voltage clamp of transducer MI400 were connected directly to the phase conductors of the network while the current exceeded the value of 5 A. The measurement was performed indirectly using a current transformer MSZ1576 that can measure AC currents from 15 A to 600 A which converts them into the current of up to 5 A at secondary.

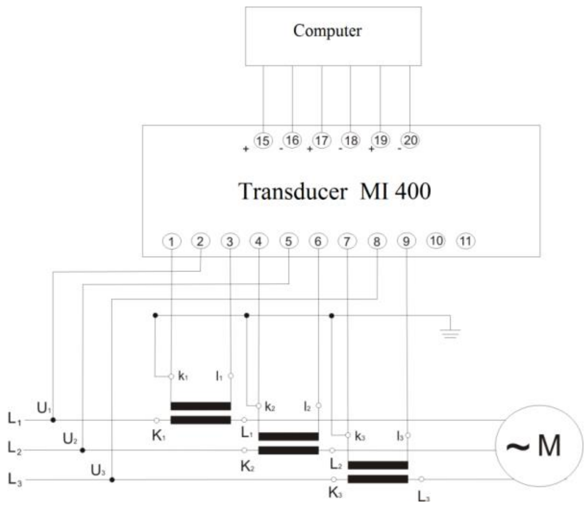

Fig. 1 Electrical diagram of the system for measuring power

The measuring transducer was connected to the data acquisition card NI PCI 6024 in the computer, and it was controlled using LabVIEW. In LabVIEW a program was created to collect 100 samples at each of the three channels with a sampling rate of 2000 S/s. The collected blocks of 100 samples were averaged in order to reduce the noise of the useful signal which yields effective 20 S/s on each of the three channels. The measured values were shown in the power-time graphs, and were recorded in the corresponding file. After the setting system the control of the work was carried out in the conditions similar to those expected during the measurement. The active power was changing depending on the load. The reactive power was almost constant, only little changed during the load changes. The apparent power was changing as it depends on the vector sum of active and reactive power. Although to us the most interesting was the active power that is performing the work, it was decided to use apparent power for the analysis to take into account the small but existing changes in reactive power load in the comparisons.

When the motor was started and reached the full rotation speed it consumed a certain power from the electric network. After the increasing the load, the consumed power increased and after the crushing the sample returned to the original level, the idle power. The energy used for the crushing of the individual sample equals the total energy consumed minus the energy in idle crusher from the moment of increasing load until the moment of the fall of the power level to idle power. The principle is shown in Fig. 2 where the energy consumed for the crushing is represented by the area under the power curve and above the idle power. From the display of measurement data (as in Fig. 2) we can also read the start time of the crushing t_p and end time of the crushing t_k.

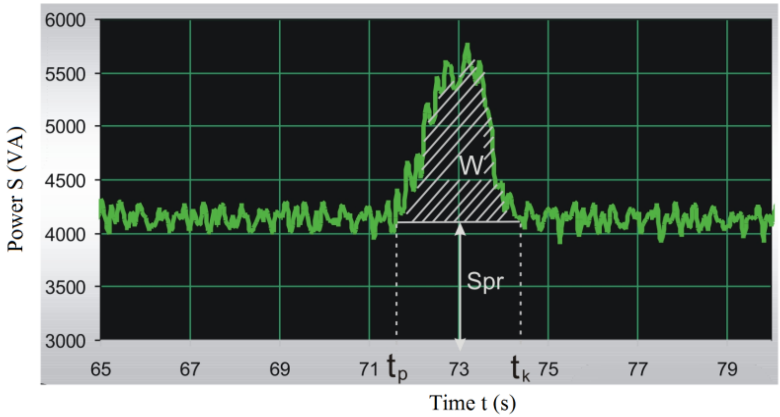

Fig. 2. Dependence of apparent power on time during crushing of individual sample

In Fig. 2, it can also be observed a change of power in the idle crusher (influence of noise in the measurement system), accordingly for each measurement mean values of idle power were calculated. Crushing energy *W* was calculated as the area with the use of numerical integration of the expression (Eq. 2):

$$W = \sum_{i=t_p}^{t_k} \frac{1}{2}\left[\left(S_i - S_{pr}\right) + \left(S_{i+1} - S_{pr}\right)\right] \cdot \left(t_{i+1} - t_i\right) \tag{2}$$

where:

W – crushing energy (VA)
t_p – start of crushing (s)
t_k – end of crushing (s)
S – apparent power (VA)

S_i – apparent power in i-th point (VA)
t_i – time in i-th measurement point (s)
S_{pr} – average idle power (VA).

A jaw crusher is a device that crushes only 50% of the time, and the crushing occurs only when a movable jaw is approaching the stationary jaw while when the movable jaw is leaving the stationary jaw the discharge of the crushing area is performed. Therefore, crushing of one sample requires more cycles of crushing i.e. approaching the moving jaw to the stationary jaw (Fig. 3).

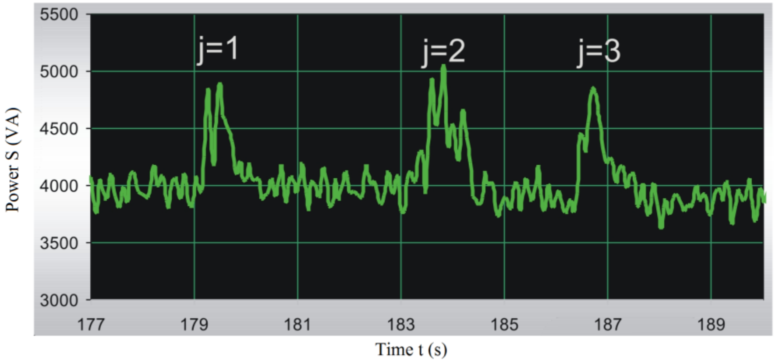

Fig. 3. Crushing sample in more cycles sample

Therefore, it is necessary to add up all the cycles according to Eq. 3 to determine the total energy required for crushing of one sample.

$$W = \sum_{1}^{j}\left(\sum_{i=t_p}^{t_k}\frac{1}{2}\left[\left(S_i - S_{pr}\right)+\left(S_{i+1}-S_{pr}\right)\right]\cdot\left(t_{i+1}-t_i\right)\right) \tag{3}$$

where j is the number of crushing cycles for the individual sample.

Upon the completion of the crushing the grain size analysis of crushed material was conducted. The statistical analysis of the measured energy determined the influence of individual mechanical properties of rocks on the crushing energy.

Results and discussion

The results of laboratory determination of mechanical properties of rocks are presented in Table 2. The data obtained by analyzing the results from the consumption of energy and time for the crushing of individual samples in the laboratory crusher are shown in Table 3. When comparing Tables 2 and 3, it is evident that the energy consumed for grinding samples varies depending on the type of rock. The samples of igneous rock spilite and diabase from the quarries of Kremesnica, Brensberg, Zervanjska and Jelenje vode showed much higher crushing energy consumption compared to the samples of limestone from the quarry of Belaj and Spica, and the lowest energy was spent for dolomite samples from the quarry of Ivanec. The samples used for the crushing were of different sizes; hence the crushing energy and time are expressed per unit mass of the crushed sample kJ/kg or s/kg.

The data obtained by direct measurement of specific crushing energy as described in this paper are not available in literature. In other papers, the crushing energy was not measured directly on crusher's motor. Donovan (2003) calculated the specific crushing energy from high energy crushing test. According to the results presented by Donnovan, the specific crushing energy for igneous rocks (granite, diabase, metabasalt) is in the range of 0.828-1.980 kJ/kg. For the sedimentary rocks (Siltstone) the specific crushing energy is approximately 1.26 kJ/kg.

Tosun and Konak (2014) measured power consumption of jaw crusher during crushing of limestone rocks. The specific crushing energy for the limestone rocks ranged between 1.012-3.298 kJ/kg. According to Refahi et al. (2009), the specific crushing energy for igneous rocks (granite) was around 1.5 kJ/kg while it was less for limestone, i.e. around 1.0 kJ/kg. Besides the measuring, the specific energy consumption was determined using numerical simulations. Refahi et al. (2009) also used a discrete element method to model the crushing behavior of some rocks with different mechanical properties in a laboratory jaw crusher. According to the authors, there is a difference between the Bond and wall energy varying from 2.7% for the lowest-strength rock (spherical limestone rock) to 26.5% for the hardest rock (spherical biotite rock) and from 37.8% for the lowest-strength cubic rock to 56.7% for the hardest cubic rock. Consequently, the Bond equation does not seem to be a suitable method for estimating fracture energy of a single cubic and/or a single spherical rock.

In this paper, the specific crushing energy for diabase ranged between 2.56-4.09 kJ/kg while lower values of the specific energy were obtained for sedimentary rocks ranging between 1.16-1.93 kJ/kg (Table 3).

Table 2. Results of laboratory tests of physical and mechanical properties of rocks

Open pit	Type of rock	Bulk density (kg/m^3)	Compressive strength (MPa)	Tensile strength (MPa)	Schmidt hardness	Fracture toughness II ($MN/m^{1.5}$)
Ivanec	Dolomite	2810	127.00	6.31	61.00	2.23
Belaj	Limestone	2650	135.20	7.01	59.00	2.35
Spica	Limestone	2660	122.20	10.62	53.00	3.02
Kremesnica	Spilite	2870	178.60	11.36	62.00	3.24
Jelenje vode	Diabase	2910	178.06	12.83	63.00	4.14
Brensberg	Diabase	2930	189.90	13.11	60.00	4.12
Zervanjska	Diabase	2940	199.80	14.62	61.00	4.28

Table 3. Results of laboratory tests of crushing energy and time

Crushing of individual samples					
Quarry	Type of rock	Total mass of samples (kg)	Total crushing time (s)	Specific crushing time (s/kg)	Specific crushing energy E_c (kJ/kg)
Ivanec	Dolomite	5.04	15.47	3.06	1.16
Belaj	Limestone	4.94	18.95	3.82	1.93
Spica	Limestone	4.83	12.25	2.53	1.65
Kremesnica	Spilite	5.55	19.70	3.55	3.45
Jelenje vode	Diabase	5.46	27.59	5.04	2.56
Brensberg	Diabase	5.15	21.34	4.21	3.51
Zervanjska	Diabase	4.34	19.34	4.55	4.09
Crushing of multiple samples simultaneously					
Quarry	Type of rock	Total mass of samples (kg)	Total crushing time (s)	Specific crushing time (s/kg)	Specific crushing energy E_c (kJ/kg)
Ivanec	Dolomite	6.07	17.07	2.82	1.09
Belaj	Limestone	6.10	12.83	2.10	1.64
Spica	Limestone	-	-	-	-
Kremesnica	Spilite	-	-	-	-
Jelenje vode	Diabase	5.91	15.72	2.64	1.52
Brensberg	Diabase	-	-	-	-
Zervanjska	Diabase	8.12	8.67	1.06	4.25

Due to the fact that the specific energy was calculated on the basis of crushing energy of individual samples, the measurements were repeated by crushing larger number of samples simultaneously. Test results obtained by measuring the crushing energy of larger number of samples are also shown in Table 3. As can be seen from Table 3 that the specific energy is approximately equal in crushing of individual samples and in crushing of several samples simultaneously while the specific crushing time reduced with the higher number of samples. This confirms that the specific energy does not depend on the amount of material that is crushed but on physical and mechanical properties of rocks.

The statistical analysis of the results determined the empirical dependence of crushing energy on certain mechanical properties of rocks (Table 4). From the statistical analysis it can be concluded that the specific crushing energy depends mostly on the compressive strength. Namely, the principle of comminution depends on the crusher construction; we can observe more crushing modes, one of which is predominant (Slokan 1969). In the jaw crusher the main mechanism of comminution is pressure, i.e. the comminution comes primarily from squeezing. Therefore it is logical to expect that compressive strength will have the greatest influence on crushing energy.

Table 4. Empirical dependence of specific energy of crushing on mechanical properties of rocks

Mechanical properties	Regression equation	Coefficient of determination	Maximum deviation (%)
Bulk density ρ_v (kg/m^3)	1. $E_c = 0.0065\rho_v - 15.778$	$R^2 = 0.541$	117.95
Uniaxial compressive strength σ_c (MPa)	2. $E_c = 0.032\sigma_c - 2.568$	$R^2 = 0.900$	30.29
Tensile strength σ_V (MPa)	3. $E_c = 0.2949\sigma_v$ - 0.5744	$R^2 = 0.713$	55.99
Fracture toughness K_{IIc} (MN/m$^{1.5}$)	4. $E_c = 1.024K_{IIc} + 0.799$	$R^2 = 0.651$	39.03
Hardness determined by Schmidt hammer H	5. $E_c = 0.1378H - 5.624$	$R^2 = 0.171$	139.6

Table 4 shows that fracture toughness and tensile strength also significantly affect the crushing energy. Some authors (Bearman 1991; Donovan 2003) also concluded that the above properties have a significant influence on the crushing energy. In addition, it is evident that the hardness has only a slight effect and bulk density has not such a significant impact. It was expected that the bulk density would indicate a greater impact since it is known that it is directly related, not only with the mineral composition but also with porosity and the number of cracks and voids in the material. The mineral composition has a greater role in influence of bulk density while cracks and voids within the samples did not play a major role due to the fact that the samples for testing were obtained by coring.

Since it is evident from the performed analysis that there is a considerable influence of a number of tested physical and mechanical properties on crushing energy, a multiple regression analysis of simultaneous influence of multiple properties was conducted.

Table 5 shows the results of the analysis for the combination of properties that provide the largest and smallest maximum absolute deviation of the specific energy, calculated using regression equations from the measured values. It appears from the indicators of reliability of multiple regression analysis that on the specific crushing energy the biggest common effect is provided by all the tested physical mechanical properties of rocks (Table 5, regression Eq. 12). Additionally, this dependence showed the smallest maximum deviation from the measured values of specific energy (1.3%). However, testing dependence of the specific energy on the combination of three studied properties of rocks already yielded a significantly small maximum deviation of the calculated energy from the measured values. The smallest maximum deviation of specific energy calculated using the three studied properties of rocks was obtained using equation on dependence of the energy on the uniaxial compressive strength, fracture toughness and hardness (5.4%). That is also evident from Fig. 4 which shows the highest and lowest maximum deviation from measured values of the specific crushing energy calculated according to the regression equations shown in Tables 4 and 5.

Table 5. Multiple regression analysis of dependence of crushing energy E_c on physical and mechanical properties of rocks

Regression equation	Regression summary for dependent variable: Specific energy, E_c (kJ/kg)	Maximum deviation (%)
6. E_c= -15.37+0.0082ρ_v –0.086H	R=0.757; R^2=0.573; Adjusted R^2=0.359; F(2,4)=2.68; p<0.183; Std. Error of estimate: 0.877	107.5
7. E_c= 1.758+0.0375σ_c -0.087H	R=0.97; R^2=0.943; Adjusted R^2=0.914; F(2,4)=32.82 p<0.0033; Std. Error of estimate: 0.321	16.0
8. E_c= -6.06+0.001ρ_v +0.829K_{IIc} +0.033H	R=0.827; R^2=0.683; Adjusted R^2=0.367; F(3,3)=2.159 p<0.272; Std. Error of estimate: 0.871	48.2
9. E_c= 4885+0.059σ_c -0.733K_{IIc} -0.156H	R=0.996; R^2=0.992; Adjusted R^2=0.985; F(3,3)=128.94 p<0.001; Std. Error of estimate: 0.136	5.4
10. E_c= -7.977-0.0002ρ_v +0.7σ_v -1.608K_{IIc} +0.148H	R=0.917; R^2=0.841; Adjusted R^2=0.522; F(4,2)=2.64 p<0.293; Std. Error of estimate: 0.756	25.6
11. E_c= 6.138-0.0009ρ_v +0.06σ_c -0.674K_{IIc} -0.141H	R=0.997; R^2=0.994; Adjusted R^2=0.981; F(2,4)=78.722 p<0.013; Std. Error of estimate: 0.151	4.5
12. E_c= 4.397-0.001ρ_v +0.053σ_c +0.17σ_v -1.108K_{IIc} -0.095H	R=0.9997; R^2=0.9994; Adjusted R^2=0.996; F(5,1)=326.796 p<0.042; Std. Error of estimate: 0.066	1.3

where:
R Pearson correlation coefficient
R^2 coefficient of determination
Adjusted R^2 : adjusted coefficient of determination
F(2,4) F-distribution
p probability value.

Table 6. Results of grain size analysis of crushed samples

Class (mm)	Average share of class (%)						
	Ivanec	Belaj	Spica	Kremesnica	Brensberg	Zervanjska	Jelenje vode
+32	8.11	0.00	4.46	4.45	3.52	4.88	0.98
32/16	46.56	52.18	46.90	53.73	57.67	56.54	59.06
16/8	24.93	26.02	26.21	24.39	20.89	20.22	21.62
8/4	9.06	8.90	9.49	7.44	6.65	6.78	7.68
4/2	5.52	5.95	6.30	4.63	4.48	4.70	4.83
2/1	2.86	3.25	3.21	2.22	2.63	2.72	2.64
-1	2.96	3.70	3.42	3.15	4.16	4.16	3.20

Upon the completion of the crushing, grain size analysis was conducted on the crushed samples with sieve size openings of 32, 16, 8, 4, 2, and 1 mm. From Table 6, it is evident that the share of each class varies depending on the type of rock. It can be seen that the share of larger classes (+32 mm and 32/16 mm) is higher in igneous rock (Kremesnica, Brensberg, Zervanjska, Jelenje vode) in comparison to the sedimentary limestone and dolomite (Ivanec, Belaj, Spica), and in the middle classes (16/8, 8/4 and 4/2 mm) it is the other way around. The share of smaller classes is more or less uniform for all rock types. Jaw crusher crushes materials by squeezing (pressure), and compared to other crushers due to friction effects of the jaw, gives a slightly higher proportion of dust.

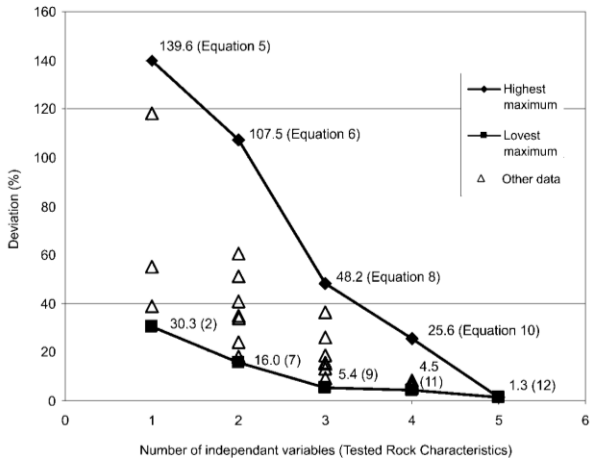

Fig. 4. Calculated specific energy deviation from measured values analysis

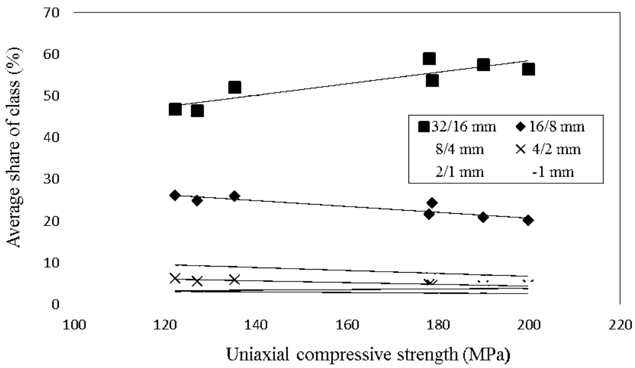

Fig. 5. Dependence of share of classes on uniaxial compressive strength

Figure 5 shows the dependence of share of classes on the uniaxial compressive strength. The diagram shows that the increasing uniaxial compressive strength increases share of the class 32/16 mm, and reduces the share of class 16/8 mm, 8/4 mm and 4/2 mm while in class 2/1 mm and -1 mm there is no noticeable dependence on pressure strength. Considering the fact that the jaw crusher gives a larger proportion of dust due to its crushing mode (squeezing and abrasion), i.e. smaller classes compared to the other crusher, the mass proportion of small classes (2/1 mm and -1 mm) is approximately the same and varies ranging from 5.37 % to 6.95 %. Other properties of the rocks showed no significant effect on the share of each class. Thus, rocks with a higher uniaxial compressive strength are "harder" to crush resulting in an increased share of larger particles and the need to use more energy for crushing.

Conclusions

In this paper, a measuring system was developed, which enables a direct measurement of power of the jaw crusher electromotor. The specific crushing energy was determined based on the difference of the energy used in crushing samples and energy used by the idle jaw crusher. According to the test results, obtained by crushing the individual samples and crushing multiple samples at the same time, the influence of the quantity of material that is crushed is negligible. Accordingly, it can be concluded that the quantity of material does not affect the specific crushing energy and that the power consumption for crushing in the jaw crusher depends on the mechanical and physical properties of the crushed material. The energy used for crushing depends on the type of rock, and is higher for igneous rocks than for limestone and the lowest is for dolomite.

Based on the empirical dependence of the energy on the individual properties of rocks further conclusions are summarized as follows:

– specific crushing energy depends mostly on the compressive strength,
– fracture toughness and tensile strength also significantly affect the crushing energy,
– the impact of bulk density is not large while hardness has only a minor impact.

Due to the fact that the effect of the tested properties of rocks on the specific energy of rock crushing was observed, a multiple regression analysis of their simultaneous influence was carried out. Using the obtained regression equations, we performed an analysis of the deviation of the specific crushing energy obtained by computation from the measured values. The smallest maximum deviation was obtained for the equation of dependence of the specific energy on all investigated properties of rocks while a significantly little deviation was obtained by expressing dependence on only three examined properties i.e. uniaxial compressive strength, fracture toughness and hardness.

By exploring the dependence of the particle sizes of crushed samples on the mechanical properties of rocks it was found that the increasing uniaxial compressive strength of crushed material increases the proportion of larger particles, while other properties have no effect.

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