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IMPACT OF ROCK HARDNESS ON FRAGMENTATION BY HYDRAULIC HAMMER AND CRUSHING IN JAW CRUSHER

UTJECAJ TVRDOĆE STIJENE NA USITNJAVANJE HIDRAULIČNIM ČEKIĆEM I NA DROBLJENJE U ČELJUSNOJ DROBILICI

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Abstract

The physical and mechanical characteristics of intact rocks depend on the way of their formation, sustained deformations and the process of wearing a specific rock has been exposed to. These characteristics have a rather high influence on the technological process of extraction and dressing of mineral raw materials. However, the mechanical characteristics of rocks due to use of explosives for their extraction in the open pit have a more significant impact. The rock blocks extracted by blasting which are larger than the opening of the primary crusher are usually fragmented by hydraulic hammer.

The paper presents the results of the testing of impact of rock hardness on fragmentation of rocks by means of hydraulic hammer and during crushing in jaw crusher. The testing was carried out on the rock samples from five quarries. According to the obtained results the hardness has a considerably larger impact on the fragmentation energy by hydraulic hammer than on the crushing energy in jaw crusher.

Sažetak

Fizičko-mehaničke značajke intaktne stijene ovise o načinu postanka, pretrpjelim deformacijama i procesu trošenja kojima je pojedina stijena bila izložena. Ove značajke imaju velik utjecaj na tehnološki proces dobivanja i oplemenjivanja mineralnih sirovina. Međutim, puno veći utjecaj imaju izmjenjena fizičko-mehanička svojstva stijena uslijed upotrebe eksploziva za njihovo otkopavanje pri površinskoj eksploataciji. Blokovi stijena dobiveni miniranjem koji su veći od ulaznog otvora primarne drobilice obično se usitnjavaju hidrauličnim čekićem. U radu su prikazani rezultati ispitivanja utjecaja tvrdoće stijena na usitnjavanje stijena hidrauličnim čekićem i tijekom drobljenja u čeljusnoj drobilici. Ispitivanje je provedeno na uzorcima stijena iz pet kamenoloma. Rezultati su pokazali da tvrdoća ima znatno veći utjecaj na energiju usitnjavanja hidrauličnim čekićem nego na energiju za drobljenje u čeljusnoj drobilici.

Introduction

The production of building crushed stone represents a considerable part of the production of mineral raw materials in the Republic of Croatia. Building crushed stone was until 2004 extracted on 250 exploitation fields according to the records of the Ministry of Economy, Labour and Entrepreneurship (Krasić, D., 2006). Principally, it is extracted from rock massif by blasting. The blasted rock mass is transported to separation where the stone is usually beneficiated by the crushing and sieving processes. The blasted rock mass contains oversized rock blocks, which are actually stone pieces larger than the opening of the primary crusher and which should have been fragmented before crushing. Oversized blocks are today almost always fragmented by hydraulic hammers. They have been frequently applied due to their numerous advantages compared to the secondary blasting – there is no stoppage of the working process, there is no stone scattering, the costs are lower, etc. However, since the beginning of their application there have been almost no testing, neither any attempts to better understanding and determination of the mechanical characteristics of rocks, which affect the use of energy upon crushing of oversized blocks.

Crushing is the process of fragmentation mineral grain aimed at achieving a certain grain size distribution, grain shape and mineral liberation (Salopek & Bedeković, 2000). The quality of building crushed stone is evaluated on the basis of the physical and mechanical characteristics, the grain size distribution and the grain shape. The co-efficient of energy use is rather low and rarely reaches 1% (Slokan, 1969), whereas the rest of the energy is used for elastic and plastic deformation and the loss of energy in crusher. Accordingly, the fragmentation process is very expensive and affects the complete mining activities. Therefore, the attempts of better understanding of the affecting values on the processes of stone fragmentation are justifiable.

Theoretical consideration

The rock characteristics largely affect the energy needed for their fragmentation from blasting, subsequent fragmentation of oversized blocks by hydraulic hammers to crushing in the process of stone refining. The explosive energy during blasting is used up on fragmentation, vibration (seismic waves) and forward movement of blasted rock mass. It has been proved in practice that blasting affects the further processing of mineral raw materials. The use of larger quantities of explosives and the explosives with a higher detonation speed will reduce the resistance of raw materials to crushing and fragmentation (Nielsen & Malvik, 1999).

There are two important impacts of blasting on fragmentation. The first 'visible' one is the grain size distribution of the blasted rock mass and the second 'invisible' one is the creation of micro-cracks in some stone pieces (Workman & Eloranta, 2003). The efficient blasting in terms of energy use includes the use of a small quantity of explosives, which at the same time will result in the optimum rock fragmentation and thus enable higher security due to the minimum loss of energy on seismic waves and forward movement of material. However, such a process results in a smaller number of micro-cracks within the bullet of the blasted stone material, which means higher energy use for further fragmentation. Accordingly, it is obvious that the fragmentation processes of stone material are affected by the physical and mechanical characteristics of intact rock material and even more by the changed physical and mechanical characteristics of stone due to its extraction by blasting.

The number and size of micro-cracks within the rock material caused by the energy of explosives directly affects the reduction of all mechanical characteristics of the material. A large number of authors have tested the impact of various mechanical characteristics of rocks on the fragmentation energy (Hofler, 1990; Bearman, et.al., 1991; Bourgeois, et.al., 1992; Duthoit, 2000; Donovan, 2003). The researches of impact were conducted in order to find a specific rock characteristic which would enable easier choice and dimensioning of machinery for fragmentation taking into consideration the determined efficiency.

The Schmidt rebound hardness of rocks is the characteristic which is due to its speed and simplicity of testing often applied in practice. A number of testings have proved the connection between the hardness and other mechanical characteristics such as uniaxial compression strenght, Young's modulus, etc. (Yasar & Erdogan, 2004). Besides, in many papers the Schmidt rebound hardness has been directly linked with the efficiency of the mechanical comminution of rock upon excavation (Poole & Farmer, 1978.; Morgan, et.al., 1979; Howart, et.al., 1986; Bilgin, et.al., 1992; Goktan & Gunes, 2005).

The paper presents the results of the testing of hardness impact on the stone fragmentation by hydraulic hammer and upon crushing in the laboratory crusher.

Testing of Schmidt rebound hardness

In order to test the impact of hardness on fragmentation of stone by hydraulic hammer and crushing in a jaw crusher the stone samples were selected from various rocks in five different quarries: «Kremešnica» near Lasinja, «Vukov Dol» near Kašina, «Belaj» near Karlovac, «Brenzberg» near Orahovica and «Ivanec» near Zaprešićki Ivanec.

In the testing of rebound hardness the Schmidt hammer was used, which was initially invented as the instrument for testing of compression strength of concrete. The Schmidt hammer (Figure 1.) consists of the housing with the piston which through release of the spring in the hammer housing strikes against the anvil of the elongated and cylindrical shape which is in contact with the tested sample. The rebound value of the piston is recorded on the measuring scale in the hammer body. The magnitude of rebound represents the measure for material hardness which is tested. The samples used in the testing of hardness were obtained through drilling with the laboratory drilling machine of the stone blocks from the blasted rock material on the locations of the above stated quarries.

Figure 1 Schmidt hammer
***Slika 1**. Schmidtov čekić*

The testing of the Schmidt rebound hardness was carried out in the Laboratory for Mining Machines of the Faculty of Mining, Geology and Petroleum Engineering in Zagreb (Kujundžić, 2002) according to the method suggested by the International Society for Rock Mechanics (ISRM, 1978.; Goktan, R. M., Ayday, C., 1993). The obtained results are presented in the Table 1.

Table 1 Results of testing of Schmidt rebound hardness
***Tablica 1**. Rezultati ispitivanja Schmidtove tvrdoće*

Quarry	Rock	Rebound value of Schmidt hammer (ISRM)
«Kremešnica»	Spilite	62
«Vukov Dol»	Marble	54
«Belaj»	Limestone	59
«Brensberg»	Diabase	60
«Ivanec»	Dolomite	61

Measuring Impact Energy on Fragmentation of Rock Blocks by Hydraulic Hammer

The measuring of the energy needed for fragmentation of oversized stone blocks was carried out in situ in five quarries stated in the Table 1. The in situ measurements comprised the determination of the volume of randomly selected blocks which remained after production blasting, including the measuring of their length, width and height with a measurement tape. The measuring of time was performed upon crushing in order to fragment the block, the volume of which was previously determined, to the required granulation by hydraulic hammer.

This refers to the effective time of fragmentation without the time needed for adjusting the block. The used up impact energy was calculated by means of technical data of hydraulic hammers i.e. the energy of the single impact and the average number of impacts per minute specifically for each hammer on each tested location.

On the grounds of the above stated measurements the statistical analysis of the interdependence of the use of impact energy and the block volume for each rock type i.e. measurement location was conducted. The following correlation interdependencies have been obtained (Kujundžić, 2002):

«Kremešnica»: $E = -31.7269452 + 329.096176 \cdot V$ (1)

«Vukov Dol»: $E = -968.9222 + 2497.2587 \cdot V$ (2)

«Belaj»: $E = -657.330353 + 1755.02622 \cdot V$ (3)

«Brenzberg»: $E = 73.2522238 + 463.507594 \cdot V$ (4)

«Ivanec»: $E = -31.8921493 + 380.477031 \cdot V$ (5)

whereby:
E - impact energy [kJ/m^3]
V - block volume [m^3]

In the Figure 2 are presented correlation interdependencies obtained on basis of in situ measurements.

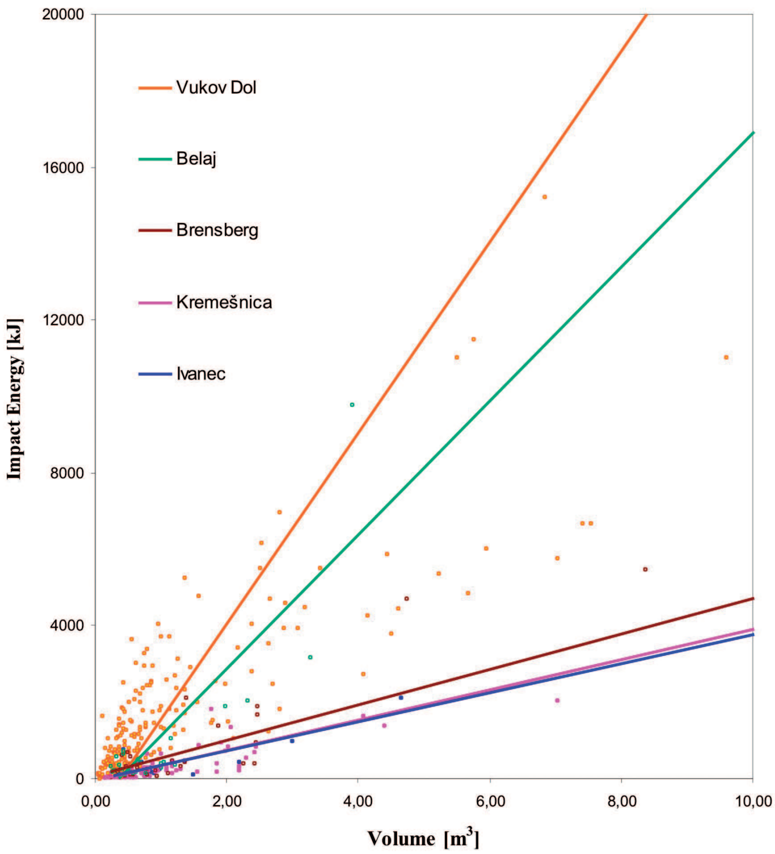

Figure 2 Correlation interdependencies of impact energy on volume of blocks
Slika 2. *Korelacijske zavisnosti udarne energije o volumenu blokova*

Measuring Crushing Energy in Laboratory Jaw Crusher

The measuring of the energy needed for crushing of stone samples was carried out on the *Loro & Parsini* laboratory jaw crusher in the Laboratory for Mineral Processing and Environmental Protection of the Faculty of Mining, Geology and Petroleum Engineering in Zagreb.

The samples, on which the Schmidt rebound hardness was tested, were used for crushing in the laboratory jaw crusher. The core obtained by drilling from rock samples in the quarries had a diameter of 63 mm and the height between 100 and 132 mm. The mass of core was approximately from 0.9 to 1.2 kg. The exact masses and sample dimensions are presented in the Table 2, whereby h represents the height, m the mass, r the diameter and V the volume of the samples.

Table 2 Dimensions and mass of samples for crushing
Tablica 2. *Dimenzije i masa uzoraka za drobljenje*

Sample number	Ivanec		Vukov Dol		Kremešnica		Belaj		Brensberg	
	h (mm)	m (g)	h (mm)	m (g)	h (mm)	m (g)	h (mm)	m (g)	h (mm)	m (g)
1	116.96	1024	134.27	1117	125.03	1118	123.07	1020	110.64	1010
2	114.56	1003	135.72	1129	121.67	1088	120.18	996	108.78	993
3	115.82	1014	123.33	1026	126.48	1131	126.45	1048	105.16	960
4	114.45	1002	121.41	1010	124.25	1111	115.83	960	136.71	1248
5	114.39	1001,5	115.32	959	123.33	1102,8	110.85	918,7	102.93	939,6
	r (mm)	V (m^3)	r (mm)	V (m^3)	r (mm)	V (m^3)	r (mm)	V (m^3)	r (mm)	V (m^3)
1	63	0.00150	63	0.00173	63	0.00161	63	0.00158	63	0.00142
2	63	0.00147	63	0.00175	63	0.00156	63	0.00155	63	0.00140
3	63	0.00149	63	0.00159	63	0.00163	63	0.00163	63	0.00135
4	63	0.00147	63	0.00156	63	0.00160	63	0.00149	63	0.00176
5	63	0.00147	63	0.00148	63	0.00159	63	0.00143	63	0.00132

Before the beginning of crushing the crusher opening was set to the size of 35 mm. The system for measurement of the used up electricity was plugged in before the start-up of the electrical engine of the crusher. After plugging-in and achieving the full number of rotations of the crusher electrical engine in neutral the crushing of samples could begin.

System of measuring

The average time of crushing of one sample was approx. 3 seconds, which initiated the development of the measuring system that can record data at the speed of 20 samples per second. The energy used up for crushing of the specific sample was measured indirectly through measuring of the electric power which the three-phase asynchronous electrical engine uses from the network. For this purpose the measuring transducer *Iskra MI 400* was used with the measuring area of 500 V voltage and 5 A electricity, which measures the apparent, working (true) and reactive powers transforming them into the voltage of ±10V at three separate exits. In each phase the voltages were approx. 400 V, so they were directly measured, whereas the electric currents were over 5 A and were measured indirectly using the measuring transformer which transforms (reduces) the primary electricity in accordance with the transformed ratio (n=3) of the EMT (Vujević, Ferković, 1996). Therefore, the measured (reduced) values of the electrical power are multiplied by three. The scheme of the system of measuring is presented in the Figure 3.

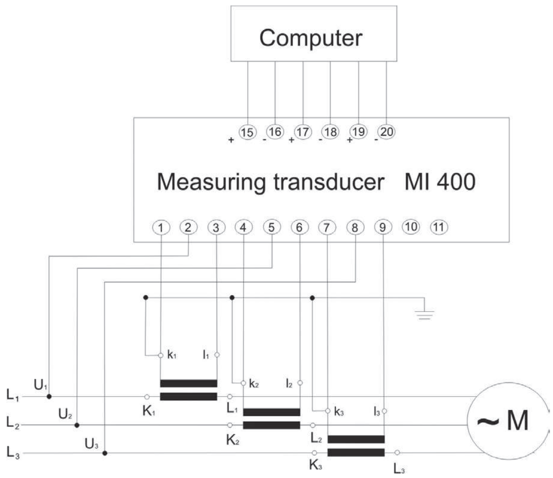

Figure 3 Electrical Scheme of System of Power Measuring
Slika 3. *Električna shema sustava za mjerenje snage*

As mentioned previously, the energy was measured indirectly through measuring of the electric power of the crusher electrical engine. In case of the alternating current the values of voltage and electrical power are changed in the time. The power in a specific moment is obtained by multiplying the instant values. There are three types of alternating current. The working power is the power of the electrical energy which is transformed in some other form of the useful energy in an energy user and equals to the product of multiplication of the line voltage, line current and phase shift between the voltage and the current:

$$P = \sqrt{3} \cdot U \cdot I \cdot \cos\varphi \tag{6}$$

whereby P is working power (W), U line voltage (V), I line current (A) and φ phase shift. Reactive power is the electrical power upon the induction load which unused goes through the energy user and returns in the form of electrical energy to the source:

$$Q = \sqrt{3} \cdot U \cdot I \cdot \sin\varphi \tag{7}$$

Apparent power equals the addition of the working and reactive powers and is calculated as follows:

$$S = \sqrt{P^2 + Q^2} = \sqrt{3} \cdot U \cdot I \tag{8}$$

Since the power changes in the time, the energy in time t equals the area under the curve (Figure 4).

$$W = \int p(t)\,\mathrm{dt} \tag{9}$$

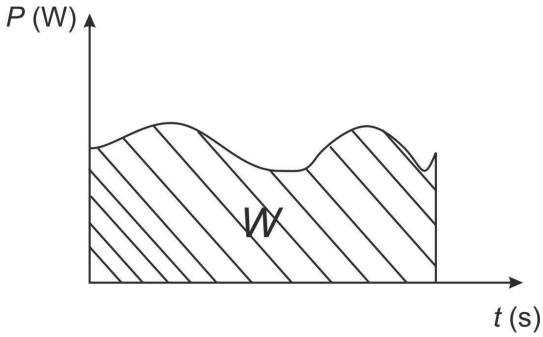

Figure 4 Diagram power-time
Slika 4. *Dijagram snaga-vrijeme*

The electric motor in the neutral position uses up the power from the network (power of the neutral position). Therefore, the energy needed for crushing is obtained from the difference between the power in the neutral position and the power during crushing. In the moment of crushing the powers instantly rise. The measuring transformer is linked with the data acquisition card NI PCI 6024E in the computer which is operated by means of the LabVIEW software. LabVIEW (**Lab**oratory **V**irtual **I**nstrumentation **E**ngineering **W**orkbench) is a graphic programming language used for collection of data, control of measuring, analysis and processing of signals and automatization. Within the LabVIEW there is a programmed routine which provides 20 samples per channel and presents the measured values on the screen in the diagram power-time and records them on hard disk in the corresponding file. The Figure 5 presents the changes of the working (green), reactive (red) and apparent (yellow) powers.

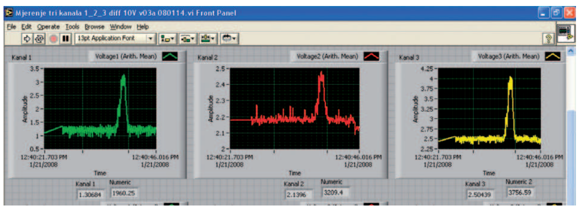

Figure 5 Graphic interface of LabVIEW application
Slika 5. *Grafičko sučelje LabVIEW aplikacije*

Analysis of results

The analysis of the results included the apparent power S which equals the multiplication product of the measured voltage U of the specific card channel, transfer ratio of SMT and the constant of the measuring transformer:

$$S = U \cdot 3 \cdot 500 \qquad (10)$$

Whereby S represents the apparent power (VA), 3 the constant of the measuring transformer and 500 the constant of the measuring transducer (VA/V). The energy used up for crushing of the specific sample equals the difference of the total used up energy and the energy in the neutral position of the crusher in a particular period. The data obtained by the LabView software were subsequently processed in the Microsoft Excel. According to the measured data a diagram time-power is created, which presents the values of the time of the beginning of crushing t_p and the ending of crushing t_k (Figure 6).

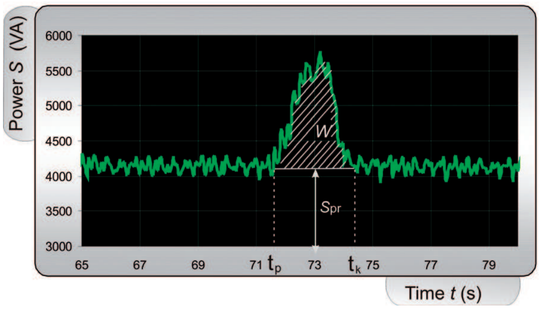

Figure 6 Diagram power-time for crushing of a specific sample
Slika 6. *Dijagram snaga-vrijeme za drobljenje pojedinačnog uzorka*

The diagram in the Figure 6 clearly shows the varying power in a neutral position of the crusher during a certain period of time. Therefore, it is necessary to calculate the average power of the neutral position. The area W, marked with hatching on the diagram, represents the energy needed for crushing which is obtained by the numerical integration according to the expression 6:

$$W = \sum_{i=t_p}^{t_k} \frac{1}{2} \left[\left(S_i - S_p\right) + \left(S_{i+1} - S_p\right) \right] \cdot \left(t_{i+1} - t_i\right) \qquad (11)$$

whereby:

W - crushing energy (VA)
t_p - time of crushing beginning (s)
t_k - time of crushing ending (s)
S - apparent power (VA)
S_i - apparent power at the i-th moment (VA)
t_i - time in i-th measurement point (s)
S_{pr} - average apparent power of neutral position (VA)

Jaw crusher operates off and on, which means that crushing begins when the movable jaw approaches the immovable jaw, whereas during their separation the space for crushing is being emptied. Therefore, more than one cycle of jaw movements is needed for crushing of one sample.

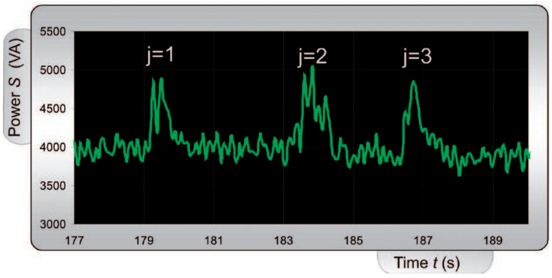

Figure 7 Crushing of sample in multiple cycles
Slika 7. *Drobljenje uzorka u više ciklusa*

Accordingly, the determination of the entire energy needed for crushing of one sample requires the addition of all the cycles, as follows:

$$W = \sum_{1}^{j} \left(\sum_{i=t_p}^{t_k} \frac{1}{2} \left[\left(S_i - S_p\right) + \left(S_{i+1} - S_p\right) \right] \cdot \left(t_{i+1} - t_i\right) \right) \qquad (12)$$

where j represents the number of crushing cycles of a specific sample. The calculation according to the formula 7 Microsoft Excel calculated the energies used up for crushing of specific samples. The obtained results in Microsoft Excel were checked by numerical integration using the software Mathematica 4.1.

Results and discussion

The impact energy needed for fragmentation of the oversized block of the presumed volume of 1 m^3 for all rock types i.e. locations of measuring has been calculated by means of the correlation interdependence (1) to (5) and the results are presented in the Figure 8.

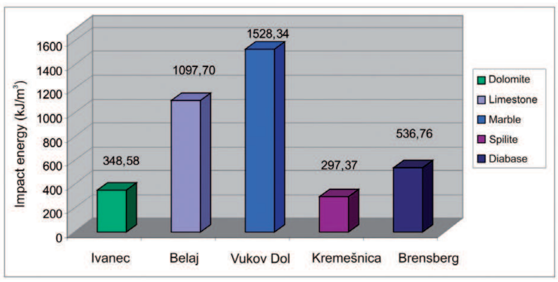

Figure 8. Impact energy of hydraulic hammers
Slika 8. *Udarna energija hidrauličnih čekića*

It is visible that the highest impact energy was used up for fragmentation of oversized blocks of marble in the quarry of Vukov Dol, whereas the lowest energy was used up for spilite in the quarry of Kremešnica.

The results of the measured energy used up for crushing of various types of rocks in the jaw crusher are presented in the Figure 9. Due to the fact that the samples prepared for in situ crushing were not of identical dimensions (Table 2), the energy is presented per volume unit of a sample [kVAs/m³] i.e. [kJ/m³]. The diagram shows that the highest energy was used up for crushing of magma rocks diabase and spilite and the lowest energy for crushing of sediment rocks dolomite and limestone.

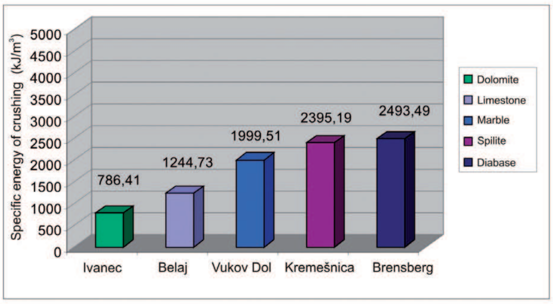

Figure 9 Specific energy of crushing of various rock types
Slika 9. *Specifična energija drobljenja pojedinih vrsta stijena*

The comparison of the results presented in the Figures 8 and 9 shows that less impact energy was used up for fragmentation of the diabase and spilite blocks by hydraulic hammers than by jaw crusher. Accordingly, it can be seen that the crushing in jaw crusher used up much more energy for all rock types than the crushing by hydraulic hammer. Such a higher use of energy for all rock types can be explained by a smaller granulation of the final product upon crushing. Upon crushing of oversized blocks by hydraulic hammer the required granulation was between 300 and 700 mm, whereas the opening of the laboratory jaw crusher upon measuring was set at 35 mm.

According to Rittinger the work needed for fragmentation of the unit of material mass is proportional to the newly created surface (Weiss, 1985; Wills, 1992). It can be concluded that through the reduced size of grains obtained through crushing it will be necessary to use more energy. The impact of the hardness on the specific energy of crushing and fragmentation by hydraulic hammer is determined by the testing of the correlation interdependence of the two-dimensional system.

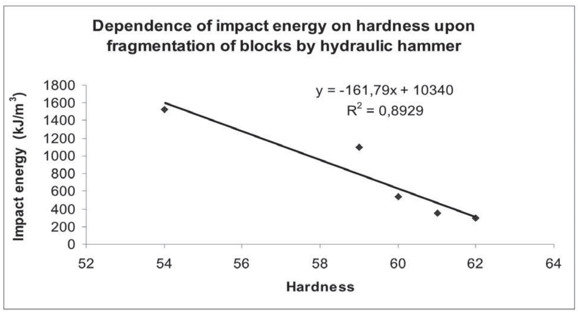

Figure 10 Dependence of impact energy on hardness upon fragmentation of blocks by hydraulic hammer
Slika 10. *Zavisnost udarne energije o tvrdoći pri usitnjavanju blokova hidrauličnim čekićem*

The Figure 10 shows the impact of hardness on the specific energy of block fragmentation by hydraulic hammer.

According to the conducted testings it can be concluded that the energy used up upon fragmentation of blocks by hydraulic hammers considerably depend on hardness (R^2 = 0.8929). The increased value of Schmidt rebound hardness causes the fall of impact energy, which means that the rocks of larger hardness will need less impact energy for fragmentation of blocks, which is logical due to the fact that brittle and hard materials (e.g. glass) have a low resistance to impact stress. In operation of hydraulic hammer this will mean that with the rocks of low hardness the working tool of the hammer will penetrate the material with the appearance of large plastic deformations without development of tensile cracks, due to which hard and brittle block materials are fastly cracked and fragmented (Kujundžić, 2002). Accordingly, the hammer will operate longer and use up more energy with the rocks of low hardness.

Compared to the hydraulic hammer it has been found (Figure 11) that hardness has a minor impact on the specific energy of crushing in jaw crusher, which is proved by a very low value of the correlation factor (R^2 = 0,0033). The reasons are probably different mechanisms of crushing between hydraulic hammer and jaw crusher. The main mechanism of crushing in hydraulic hammer is the impact. The material hardness in such a way of crushing has logically a considerable influence.

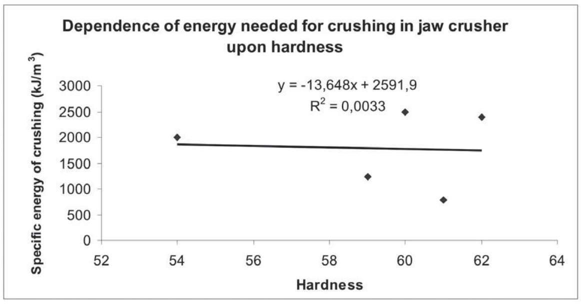

Figure 11 Dependence of energy needed for crushing in jaw crusher upon hardness
Slika 11. *Zavisnost energije potrebne za drobljenje u čeljusnoj drobilici o tvrdoći*

Due to the excentric moving of the movable jaw the crushing in jaw crusher causes the appearance of various crushing mechanisms, from which the pressure is the most important one. No matter of the fact that the Schmidt rebound hardness is frequently used in practice for the approximate determination of the pressure hardness, the above stated testings have proved that the crushing energy in jaw crusher insignificantly depends on the material hardness.

Conclusion

According to the analysed results it can be concluded that the efficiency of hydraulic hammer directly depends on the rock hardness which is to be crushed. The increased hardness of rock mass raises the efficiency of hydraulic hammer i.e. reduces the use of impact energy. During crushing of the rocks of low hardness the penetration of the working tool of hammer into the rock will cause a lot more plastic deformations, which will result in a longer operation period of hammer and consequently a larger energy use.

Contrary to this, hardness has almost no impact on the crushing energy. Therefore, it can be concluded that upon observation of the energy efficiency of crushing in jaw crusher hardness will not have a crucial impact. Further testings will have to analyse the impact of some other physical and mechanical characteristics, for example the impact of pressure hardness or maybe, due to the complex crushing mechanism emerging due to the excentric movement of the movable jaw, the combined simultaneous impact of a number of characteristics.

The specific energy of fragmentation depends on the physical and mechanical characteristics of rock and on the changed fragmentation technology, as well. This points to the fact that, depending on the fragmentation technology, the strength of the impact of specific physical and mechanical characteristics will be changed too.

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