DOI 10.31891/2307-5732-2024-339-4-64
УДК 622.271

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STUDY OF THE INFLUENCE OF THE GRANULOMETRICAL COMPOSITION OF THE EXPLODED MASS ON THE EFFICIENCY OF THE EXCAVATION PROCESS IN THE DEVELOPMENT OF BUILDING ROCKS

The purpose of the research is to analyze the degree of influence that rock mass fragmentation has on the productivity of loading equipment. To improve overburden removal operations and enhance the efficiency of excavation and loading equipment, the conditions for crushed stone quarry development were considered. The identification of research directions, which involves analyzing the current state of mining operations at quarries and reviewing literature on improving overburden removal processes under quarry conditions, allows for the formulation of goals and tasks related to the justification of a technological scheme for using cyclic equipment. An analysis was conducted on factors affecting the productivity of cyclic equipment in quarry faces. During the research, statistical methods were applied to process the results, and queuing theory was utilized for planning equipment productivity during shifts. The main focus of the study is on examining the impact of key drilling and blasting parameters on the quality of rock mass preparation, as well as the methods for calculating drilling and blasting parameters to achieve the required granulometric composition of the rock mass..

Keywords: rock fragmentation, construction materials, crushed stone production, rock mass fragmentation, excavation and loading machines.

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ДОСЛІДЖЕННЯ ВПЛИВУ ГРАНУЛОМЕТРИЧНОГО СКЛАДУ ПІДІРВАНОЇ МАСИ НА ЕФЕКТИВНІСТЬ ПРОЦЕСУ ЕКСКАВАЦІЇ ПРИ РОЗРОБЦІ БУДІВЕЛЬНИХ ГІРСЬКИХ ПОРІД

Метою даного дослідження є аналіз дослідження ступеня впливу кускуватості гірничої маси на продуктивність навантажувального обладнання. Для удосконалення розкривних робіт та підвищення ефективності роботи виймально-навантажувального обладнання розглянуто умови розробки щебеневих кар'єрів. Визначення напрямків дослідження, що пов'язане з аналізом сучасного стану гірничих робіт на кар'єрах, оглядом літературних джерел із удосконалення розкривних робіт в умовах кар'єру, дозволяє сформулювати цілі, завдання з обґрунтування технологічної схеми використання обладнання циклічної дії. Виконано аналіз чинників, що впливають на продуктивність обладнання циклічної дії у вибоях кар'єру. Під час досліджень застосовано статистичні методи обробки результатів, теорію масового обслуговування під час планування продуктивності обладнання протягом зміни. Основна частина роботи зосереджена на дослідженні впливу основних параметрів буропідривних робіт на якість підготовки гірничої маси, а також методів розрахунку параметрів буровибухових робіт на заданий гранулометричний склад гірничої маси.

Ключові слова: подрібнення гірських порід, будівельні матеріали, виробництво щебеню, кусковатість гірничої маси.

Introduction

The efficiency of the mining industry, particularly in the production of crushed stone, plays a crucial role in supporting infrastructure development and construction sectors worldwide. As one of the largest extractive industries, the production processes in this sector must evolve to meet modern economic demands. However, current technological approaches, especially those related to drilling and blasting operations, remain outdated, often adhering to regulations developed decades ago. This discrepancy leads to inefficiencies that not only affect production but also contribute to environmental degradation through the generation of excessive fines and oversized fragments in blasted rock masses.

The ability to optimize the fragmentation of rock masses is essential for improving loading productivity and reducing operational costs. Inappropriate fragmentation increases loading time, accelerates equipment wear, and negatively impacts the overall profitability of mining enterprises. Additionally, the inefficient use of explosive energy leads to an elevated production of waste materials, such as fines, which have limited utility and contribute to environmental challenges, such as increased land use for waste dumps. Given these challenges, there is a pressing need to revisit and optimize the parameters of drilling and blasting operations, with a focus on minimizing oversized fragments and fines.

Problem formulation

The construction materials industry is the largest extractive sector of the national economy, with a significant portion represented by enterprises engaged in the production of crushed stone. Currently, the technological parameters of extraction do not meet the modern requirements of the market economy. Specifically, the design of drilling and blasting operations is still based on regulations developed in the early 1980s, which were primarily aimed at achieving a strictly fixed percentage of oversized fragments in the blasted rock mass.

The transition of enterprises to self-financing imposes the task of increasing their profitability. It is well known that the cost of producing crushed stone comprises expenses for drilling, blasting operations, excavation, transportation, and crushing at the crushing and screening plant, and these costs, to some extent [1, 2], depend on the fragmentation of the rock mass. Moreover, the output of individual fractions of crushed stone is a function of the quality of rock fragmentation. Therefore, as a determining criterion in the design of drilling and blasting operations, it is necessary to establish the dependence of profit as a function of the key parameters of the technological process.

At the same time, the output of finished products at crushed stone enterprises is approximately 70% of the processed rock mass. The remaining 30% consists of fines, for which there is practically no application. These fines are transported to dumps, creating an unfavorable environmental situation. Such a high yield of fines in the production of granite crushed stone is primarily due to the inefficient application of explosive energy to the rock mass. Therefore, improving the efficiency of crushed stone production and ensuring the rational use of mineral resources through the selection of optimal parameters for drilling and blasting operations is a critical and relevant issue both from a practical and scientific standpoint.

Reducing the output of fines by 25% will significantly increase crushed stone production. This can be achieved through the proper (optimal) application of explosive energy to the granite mass, which ultimately depends on the calculation of key drilling and blasting parameters that ensure the optimal granulometric composition of the blasted rock mass.

Therefore, the issue of developing scientific and methodological foundations for the efficient fragmentation of rocks through blasting in crushed stone production is theoretically relevant and of significant importance.

Main material

The practice of excavating hard rocks shows that loading productivity largely depends on the fragmentation of the blasted rock mass.

To determine the impact of rock fragmentation on the productivity of loading equipment under operating quarry conditions, chronometric observations were conducted on the performance of excavators during the loading of rock mass into haul trucks. Using stopwatches, the time for each operation and the entire loading cycle was recorded: bucket filling, the number of bucket loads, the loading time of transport vehicles, and the swing angle of the excavator during unloading. Simultaneously, the granulometric composition of the loaded rock mass was measured directly at the excavation site using photoplanimetric methods.

As the evaluation criterion for excavator performance, productivity per hour of net operating time was adopted, as this indicator most objectively reflects the quality of fragmentation.

In analyzing the productive work of the excavator, the following indicators were recorded:

where t_{load} – the time taken to load one dump truck, including approach and departure, min; t_{rem} – the time spent removing oversized fragments, min; t_{ad} – the time for performing auxiliary operations (relocation, surface leveling), min; t_i – the time spent idle, min; G is the average load capacity of a single dump truck, tons; V_o – the total volume of oversized fragments removed after the shift, in cubic meters; and V_{total} – the total volume of the loaded rock mass, m^3.

Then we have the following:

$$V_n = \frac{V'_n}{Vt + V'_n} \cdot 100\% \qquad (1)$$

The productive working time of the excavator is equal to:

$$t_n = t_{load} + t_{rem} + t_{ad} \qquad (2)$$

And the excavation productivity:

$$Q = \frac{n \cdot G \cdot Gt}{t_{load} + t_{rem} + t_{ad}} \qquad (3)$$

where *n* - the number of loaded dump trucks.

In the analysis of the excavator's performance, an empirical dependence of the excavator's loading productivity on the output of oversized fragments was established, as shown in Fig. 1, and approximated by the following equation:

$$Q_e = \frac{2250}{3.15 + 0.32 \cdot V_H}, \text{ m}^3\text{/hour} \tag{4}$$

where V_H - the proportion of oversized fragment output, %.

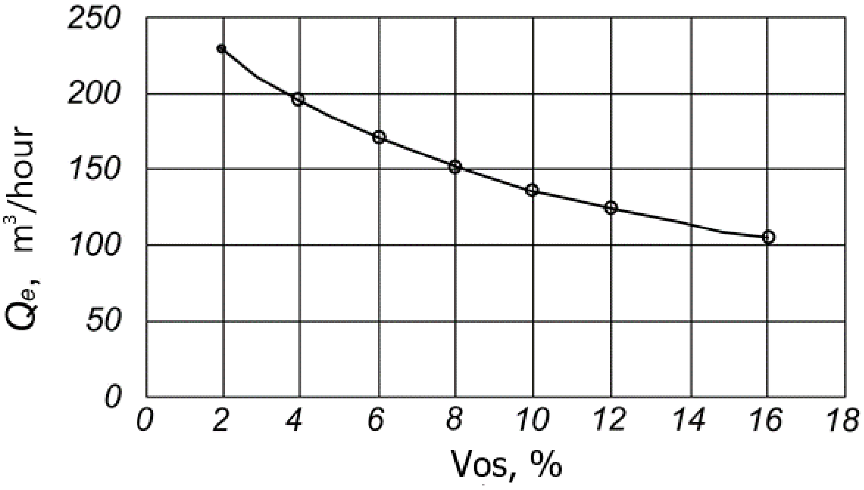

Fig. 1. Dependence of rock mass loading productivity on the output of oversized fragments

The analysis of the obtained dependence shows that reducing the output of oversized fragments from 15% to 3% doubles excavation productivity, and reducing the oversized fragments from 15% to 0% increases productivity by 2.5 times.

Additionally, the following coefficients must be considered when calculating the productivity of the excavator:

– bulldozer cleanup of vehicle access roads to the excavator: 0.97;
– conducting blasting operations during the shift: 0.97;
– watering of the excavation face during the shift: 0.96;
– operating with an excavator swing angle exceeding 14 degrees: 0.9.

In Fig. 1, the loading productivity is presented without considering the aforementioned coefficients; however, all subsequent calculations of loading productivity based on the average fragment size were carried out taking all coefficients into account.

The impact of rock mass fragmentation on the excavator's productivity is accounted for through the oversized fragment coefficient k_{of} (Fig. 2):

$$Q_e = Q_0 \cdot k_{of}, \text{ m}^3\text{/hour} \tag{5}$$

where Q_0 – the excavator's productivity in the absence of oversized fragments, m^3/year; k_{of} – the oversized fragment coefficient, calculated by the following formula:

$$k_{of} = \frac{1 - V}{1 - V_H \cdot 0{,}2} \tag{6}$$

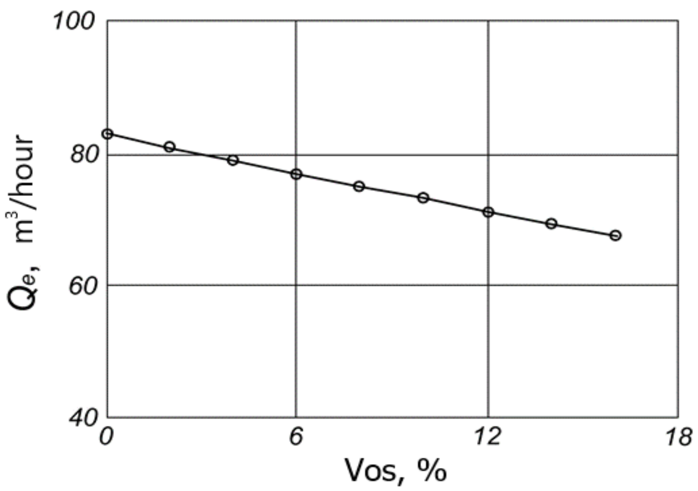

Fig. 2. Dependence of rock mass loading productivity on the output of oversized fragments

The graph shows that as the output of oversized fragments increases, loading productivity decreases by 1.5 times.

During the processing of both control and experimental blocks, it was established that the distribution of fragments in hard-to-blast rocks is uneven, and the excavator's productivity decreases on average to 30-40%.

Papers [3-5] have established the dependence of loading productivity on the fragmentation of the rock mass for the conditions at Mykolaiv Quarry, Kryvbas enterprises, Shartash Granite Quarry, and Persho-Vasylkivsky Ore Administration.

For Kryvbas enterprises [5]:

$$Q_e = \frac{1}{a_e + b_e \cdot D_{cep}}, \text{ m}^3/\text{year} \quad (7)$$

where a_e i b_e - the empirical coefficients, determined by the least squares method, are 0.00146 and 0.00924, respectively. For Mykolaiv Quarry:

$$Q_e = \frac{3600 \cdot V_a}{b_e + c_e \cdot D_{cep}}, \text{ m}^3/\text{year} \quad (8)$$

де V_a – the load capacity of BelAZ-540 and BelAZ-548 dump truck bodies, m^3; b_e i c_e – the empirical coefficients.

For Shartash Granite Quarry:

$$Q = 252 - 4.5N, \text{ m}^3/\text{year} \quad (9)$$

where N - the output of oversized fragments, %.

Since the output of oversized fragments can be determined by the granulometric distribution, which is approximated by a log-normal law, calculations were made to determine the dependence of productivity and excavation costs as a function of the average fragment size of the blasted rock mass. The obtained values of loading productivity, along with data from other researchers, are presented in Table 1 and Fig. 3.

Fig. 3 shows that a decrease in the average diameter of the blasted rock mass leads to a 40-50% change in excavator productivity. Measurements of the granulometric composition of the blasted rock mass have shown that the smallest average fragment diameter ranges from 100 to 200 mm. At this size, the technically feasible productivity of the excavator is achieved under the conditions of the given enterprises.

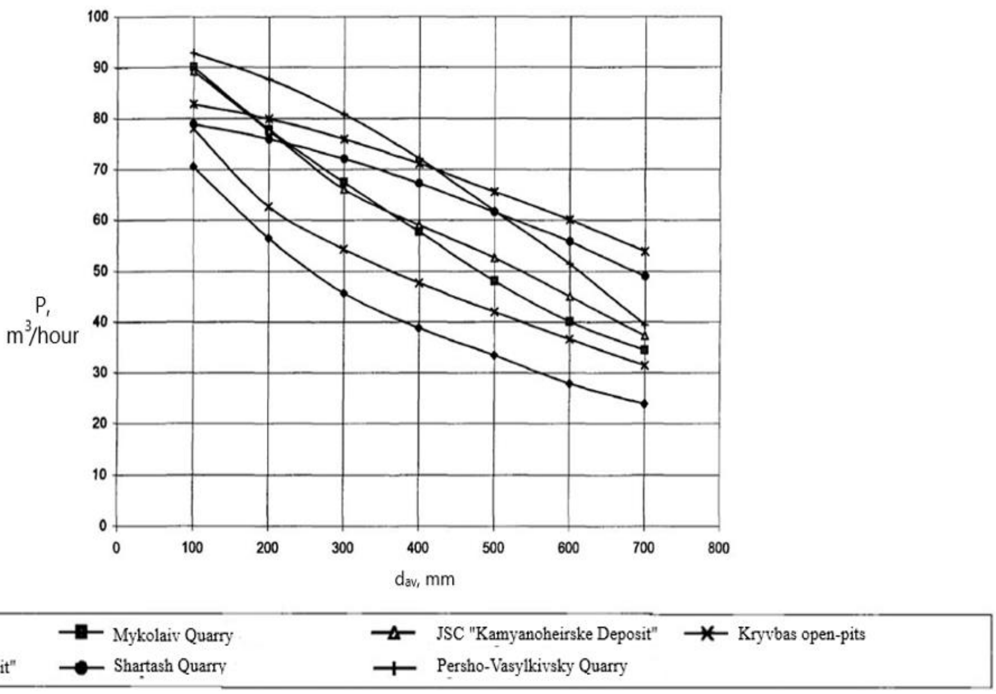

Fig. 3. Dependence of excavation productivity on the fragmentation of the rock mass

For example, at the Pivdennyi Mining and Processing Plant (PivdGZK) quarry [6, 7], the output of oversized fragments was reduced from 1.45% to 0.3%, while the annual productivity of excavators per cubic meter of bucket capacity increased by 24.6%. At Quarry No. 3 of ArcelorMittal Kryvyi Rih, the output of oversized fragments decreased from 3.6% to 0.1%, and annual productivity increased by 27.4%. Thus, improving the quality of rock fragmentation through blasting significantly increases the efficiency of loading operations.

The cost of one machine shift for an excavator remains practically unchanged, so as the excavator’s productivity increases, the cost of loading 1 cubic meter of blasted rock mass decreases (Table 2, Fig. 4).

Table 1

Research results on loading productivity.

d_{av}, mm	Mykolaiv Quarry		JSC "Kamyanoheirske Deposit"	Kryvbas open-pits	Shartash Quarry	Persho-Vasylkivsky Quarry	JSC "Granit-Kovalske"
	BelAZ-540	BelAZ-548					
100	70,6	90,1	89,3	77,9	78,85	92,82	82,83
200	56,4	77,8	77,6	62,7	75,96	87,65	79,87
300	45,7	67,5	66,1	54,3	72,12	80,75	75,97
400	38,8	57,7	59,0	47,7	67,31	72,13	71,18
500	33,5	48,1	52,6	42,0	61,54	61,78	65,56
600	27,9	40,1	45,0	36,6	55,77	51,44	60,07
700	23,9	34,4	37,3	31,5	49,04	39,37	53,82

$$C_e = \frac{C_{sh}}{Q_e} \quad (10)$$

where C_e – the cost of excavating 1 m^3 of blasted rock mass, UAH/m^3; C_{sh} – the cost of one machine shift of the excavator, UAH/shift.

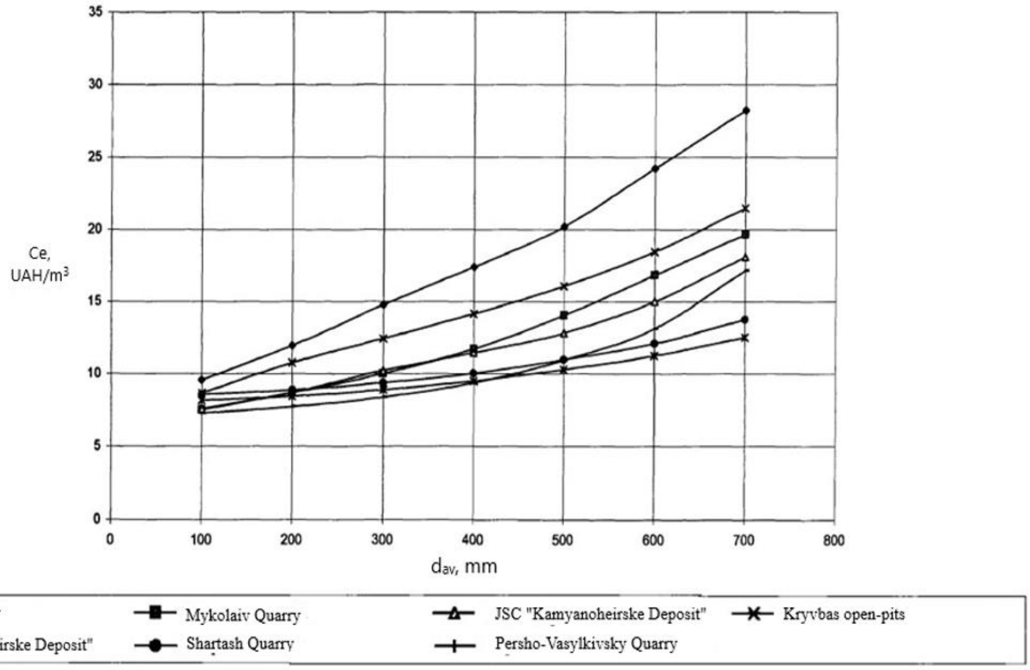

Fig. 4. Dependence of loading cost on the fragmentation of the rock mass

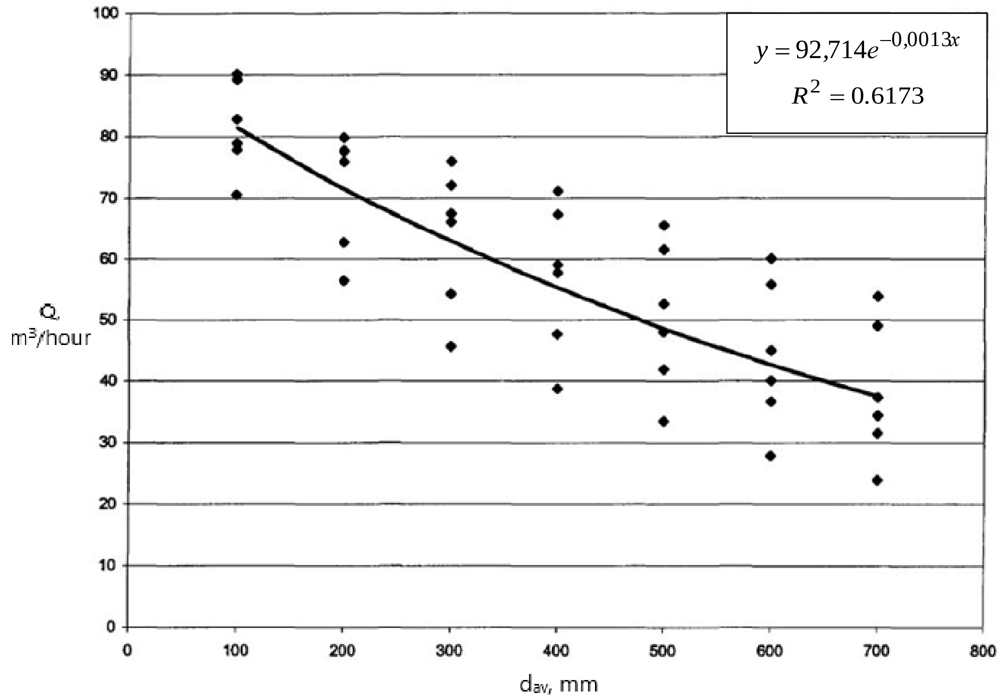

Fig. 5. Generalized dependence of the loading productivity of 1 cubic meter of blasted rock mass on the average fragment size

Table 2.

Research results on loading productivity.

d_{av}, mm	Mykolaiv Quarry		JSC "Kamyanoheirske Deposit"	Kryvbas open-pits	Shartash Quarry	Persho-Vasylkivsky Quarry	JSC "Granit-Kovalske"
	BelAZ-540	BelAZ-548					
100	9,57	7,49	7,56	8,67	8,56	7,27	8,15
200	11,97	8,68	8,71	10,77	8,89	7,70	8,45
300	14,78	10,01	10,22	12,45	9,36	8,36	8,89
400	17,41	11,71	11,45	14,15	10,03	9,36	9,48
500	20,18	14,06	12,84	16,10	10,97	10,93	10,3
600	24,20	16,85	15,00	18,45	12,11	13,13	11,24
700	28,22	19,64	18,11	21,44	13,77	17,15	12,55

The data presented above allow for constructing a general dependence of the loading productivity of 1 cubic meter of blasted rock mass on the average fragment size (Fig. 5), which is approximated by an exponential relationship:

$$y = 92{,}714e^{-0{,}0013x} \qquad (11)$$

where y - excavation productivity per 1 m^3 of rock mass, UAH/m^3; x - average fragment size, mm.

The reliability coefficient of this approximation is equal to $R^2 = 0.6173$.

Thus, a decrease in the degree of rock fragmentation leads to a reduction in productivity and, consequently, an increase in the cost of loading the blasted rock mass (by 3 to 20 times).

Conclusions and further research directions

In conclusion, it is important to highlight that the efficiency of excavation and loading processes is largely dependent on the quality of preliminary rock fragmentation during drilling and blasting operations. Reducing the proportion of oversized fragments significantly increases excavator productivity and lowers the cost of loading. The research has shown that decreasing the average fragment size of the blasted rock mass not only increases production volumes but also positively impacts environmental aspects by reducing the generation of fines that are typically sent to waste dumps.

The practical significance of these findings lies in the ability to apply the obtained dependencies to optimize drilling and blasting parameters at enterprises involved in crushed stone production. This will help reduce costs, enhance production efficiency, and mitigate the negative environmental impact.

Further research will be directed at predicting equipment performance under dynamic conditions, as well as under conditions of incomplete initial data.

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