vertical cylindrical stopes is ensured (as against the conventional columnar and chain pillars) by the ability of the pillars to have the lateral thrust with the neighbor pillars in the variant of the honeycomb mine structure, and by the most favorable shape of the structural elements of such mine—vertical cylindrical stopes which are sufficiently stable in the conditions of rock pressure (the effective stresses of the vertical cylindrical stopes flow around the rib pillars).

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UDC 622.234.42

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IMPROVING EFFICIENCY OF ROCK BREAKING USING PRE-WEAKENING OF ROCK MASS

The purpose of this study is to improve the quality of drilling and blasting operations using pre-weakening of rock mass. The approach used in the study involved pilot testing of the pre-weakening technology efficiency at the Ayak-Kodzhan open pit in Kazakhstan. The testing plan included five blasts using the standard technology and five blasts with the pre-weakening technology with subsequent change in the drilling-and-blasting parameters toward their optimization for increasing the breaking efficiency. The K-MINE: Grain Size module (developed by K-MINE, Kryvyi Rih, Ukraine) was used to determine the granulometric composition of blasted rock mass and to assess the quality of fragmentation by blasting during rock excavation. In addition, the rate of rock mass loading to dump trucks, the bench bottom condition and the slope fracturing were evaluated.

Keywords: *ore breaking, explosive, fragmentation quality, pre-weakening, blasthole efficiency ratio, burden*
DOI: *10.17580/em.2023.02.13*

Introduction

Although significant progress has been made in the scientific and technical aspects of rock fracture by blasting, many mining companies pursue improvement of blasting efficiency.

Despite advancements in the blasting technique and industrial explosives, the technical and economic characteristics of explosives somewhat fall behind the growing demands of the mining industry. Blasting accounts for up to 30% of mineral mining costs as a dominant method of fracturing large volumes of rocks. Crushing and milling are among the highest energy-consuming processes and take up to 30–60% of total energy consumption. The quality of blasting and rock fragmentation by blasting are crucial for subsequent ore processing, and are a determining factor for various technological and economic indicators.

A feature of many deposits is the variability of the physical and mechanical properties of rocks across both an area of an open pit field and a volume of blocks prepared for blasting. The current practice of standard drilling and blasting patterns in mines fails to ensure the required rock fragmentation. The yield of oversize has increased appreciably in large-block blasting [1, 2].

In fragmentation by blasting, pursuant to the process requirements imposed on fragment size composition, the top priorities are the improvement of blast efficiency and the reduction of energy lost in dissipation in the area of irreversible deformation [3–5]. Solving these tasks is associated with ensuring the explosive characteristics of the charge to be in compliance with the strength properties of rock mass, as well as with adjusting the rate of loading of rock mass by selecting the cheapest explosives with appropriate explosive characteristics in each particular case.

Recent studies and publications

Currently, there are various approaches to describing the processes of explosive rupture and to identifying the relationship between the explosive charge characteristics and the blast results.

In open pit mining, rock mass is subjected to numerous blasts and, thus, experiences systematic and periodic loading before separation and fragmentation of a certain subsoil volume by the main blast. Every next area to be blasted undergoes stressing by the previous blasts. The result of this technique of strong rock blasting and excavation is the continuously varying stress–strain behavior which yet lacks a developed real-time evaluation method [6].

Initial loading must decrease strength of rocks. For example, the ultimate tensile strength of marble is lower than in static loading and is only 9.8–68.7 MPa instead of 68.7–78.5 MPa, which can be explained by the concentration of stresses at macro- and micro-defects and dislocations, and much less energy is required for fracturing such samples.

Initial loading of rocks provides conditions for increasing the blast efficiency, and this is already observed at different velocity ratios of detonation and stress waves. In the fragmentation zone of a smaller radius, the fragment sizes are larger; on the other hand, in the fragmentation zone with a larger radius, the fragments are fine.

Since blasting in open pits is performed with multiple rows of drillholes, the effect of such blasting, even with short delays, can be considered as blasting in a half-space with a single exposed surface, especially for the last row of blastholes. Therefore, it is possible to identify the zone of compression near the charge and the zone of plastic deformation behind it, and both are within 3–5 radii of the charge [7, 8].

The quality of blasting is governed by the coarseness and uniformity of fragmentation, by the width and height of a muck pile and by the quality treatment of a bench bottom. The latter two factors have a major effect on the productivity of the subsequent rock excavation and haulage processes. The use of modern loading and transportation equipment, and mobile crushers and screeners require higher quality preparation of rock mass by blasting as it directly affects their productivity [9].

Pending issues. Drilling and blasting operations are of particular importance in mining. However, the main factor preventing growth of labor efficiency, reduction of cost and increase in production output is the low-quality and nonuniform fragmentation, which leads to a significant yield of oversize and to deviation of bench parameters from a project [10, 11]. Thus, the control over the quality and pattern of blasting in open pits is one of the crucial practical tasks. But despite the substantial scientific research in this area, until now, the point of achievability of a certain fragmentation quality in rock mass by adjustment of blasting designs and patterns yet remains topical [12–14].

Objectives. To solve this task, it is required to develop an efficient ore breaking technology, to offer theoretical validation of its applicability and to perform pilot testing.

Procedure

In this paper, the authors propose a breaking technology that involves pre-weakening of rock mass in combination with optimized blasting pattern with extra row of blastholes such that the explosion yield of the additional blastholes is lower than the ultimate tensile strength of rocks. The burden is to be found individually for each case, with regard to both geological conditions of the deposit and fracture zone radii. The distance to the additional row of blastholes and the spacing of the blastholes are selected with regard to the burden of the first row, and all primary drillholes must be equally spaced from these blastholes. In this fashion, an elastic stress wave is created so as not to fracture rocks but create initial stresses (**Fig. 1**). The first row of blastholes should be initiated after the blast wave of the additional row has passed the first row. The effect obtained through such short-delay blasting ensures interference of stress waves, which weakens the stress impact and enhances the fracture action in rock mass.

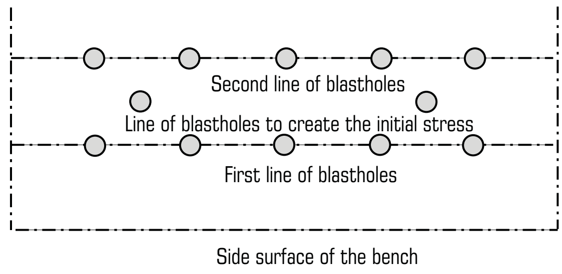


Fig 1. Proposed blasting pattern

The efficacy of the prestress technology on blasting performance was tested through a series of experimental blasts at the Ayak-Kodzhan deposit which is currently being developed by Fonet Er-Tai AK Mining LLC in collaboration with Interrin Science and Production LLP.

This deposit is situated in the Ekibastuz district of the Pavlodar Region approximately 135 km northeast of Temirtau and 85 km south of the Shiderty railway station.

Copper mineralization is localized within the subvertical brecciated tectonic zone of with intense fracturing of rocks in the North-Western direction. Rocks have widespread parallel layering.

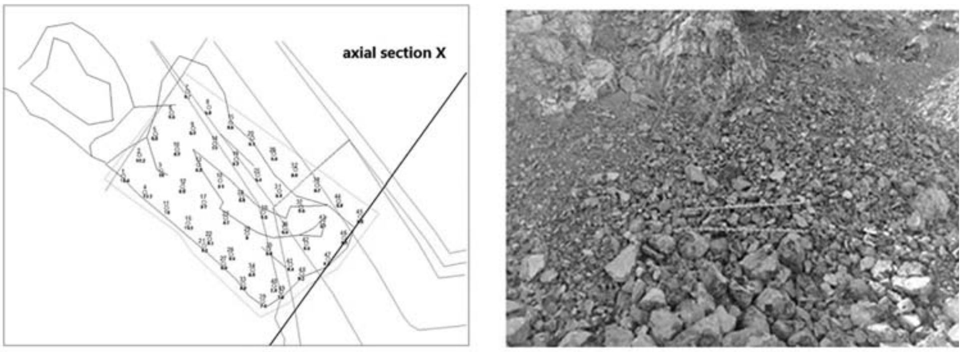
Pilot tests were conducted in the following blocks: No. 03-08, level +407–395 m; No. 03-10, level +445–435 m; No. 03-05, level +450–445 m. During the tests, ten blasts were performed, including five blasts using the common technology and five blasts with the prestress technology. The drilling and blasting design was modified during the tests to determine the optimal values for improving efficiency of breaking with the creation of stress state in rock mass.

The first reference blast was performed using a standard 4×4 m blasthole pattern without any additional holes to create prestress in rock mass **(Fig. 2*a*)**. The block volume was 6420 m^3, and the diameter of the blastholes was 165 mm. There was a total of 49 blastholes with an average length of 9.27 m, resulting in the total drilling length of 454.3 m. The blastholes were charged using the standard inverse electric initiation technique, with Igdarin EGA as the primary explosive, Petrogen P priming cartridges with the diameter of 90 mm and weight of 1.5 kg, and tamping of 20% of the blasthole length. The explosive consumption per block was 7632.24 kg, with epy powder factor of 1.19 kg/m^3. The yield per 1m of drillhole was 14.13 m^3/m.

Visual inspection of the block proved the satisfactory fragmentation quality, the break line was clearly visible, and the oversize yield was 0.8%, No overshoot of the bottom was observed, and no fractures were found on the slope **(Fig. 2*b*)**.

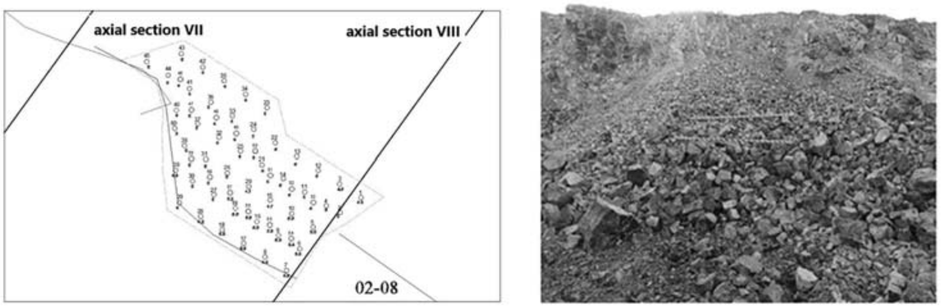
During excavation, the excavator loading rate into dump trucks increased by 10% due to the improved fragmentation.

The first experimental blast with prestress was conducted in a rock block using a regular 4×4 m pattern and with additional 14 blastholes meant to create prestress in rock mass. The block volume was 3.372 m^3, and the blasthole diameter was 165 mm. The total number of the blastholes was 60, and their average length was 5.1 m, resulting in the total drilling length of 305.8 m. The blastholes were loaded using the regular technology, with



(*a*) (*b*)

Fig. 2. Block blasting pattern (*a*) and broken muck pile (*b*). The first reference blast. Drilling pattern is 4×4 m



(*a*) (*b*)

Fig. 3. Block blasting pattern (*a*) and broken muck pile (*b*). The first experimental blast with pre-weakening of rock mass. Drilling pattern is 4×4 m

inverse electric initiation, Igdarin EGA as the main explosive, and Petrogen P priming cartridge with the diameter of 90 mm and 1.5 kg in weight. The tamping size was 20% of the blasthole length in the reference blasting and 50% of the blasthole length in the experimental blasting. The total explosive consumption per block was 4588.11 kg with the powder factor of 1.36 kg/m^3. The yield per 1 m of blasthole was 11.03 m^3/m **(Fig. 3*a*)**.

Visual inspection of the block proved the satisfactory fragmentation quality, the break line was clearly visible, and the oversize yield was 0.6%, No overshoot of the bottom was observed, and no fractures were found on the slope **(Fig. 3*b*)**.

During excavator operation on this block, the rate of loading rock mass into dump trucks increased by 10–15% due to quality fragmentation of rock mass.

The grain-size composition in muck pile and the fragmentation quality effect on excavation were evaluated using software K-Mine Granules—a product of K-Mine Company, Ukraine. Additionally, the loading speed, the slope bottom condition and the slope fracturing were assessed.

Table 1 gives the results of the other test blasts.

Results and discussions

Processing of the data of the experimental blasts allowed the dependences of the total drilling length on the blasthole pattern for the reference and proposed technologies of rock breaking (**Fig. 4**).

Table 1 shows that the change in the drilling pattern from 4×4 m to 5×5 m results in the reduction of the total drilling length in the proposed technology by 23 to 32%. However, the further increase in the drilling pattern to 6×6 m leads to an increase in the total drilling length in the proposed technology.

Powder factor is considered to be one of the main indicators in ore breaking. The comparison of the results of ore breaking in the reference and proposed technologies (see Table 1) shows that despite additional drilling of blastholes to create preliminary stress state in rock mass, the powder factor in the reference and proposed technologies is the same and ranges from 0.7 kg/m^3 to 1.08 kg/m^3 and from 0.8 kg/m^3 to 1.05 kg/m^3, respectively. Only with the 4×4 m pattern, there is an increase in the powder factor in the proposed breaking technology. Processing of the data of the experimental blasting produced the dependences of the powder factor on the blasthole pattern for the reference and proposed technologies of rock mass breaking (**Fig. 5**).

The comparison of the ore yields per 1 m of blastholes (**Table 2**) shows that with the drilling patterns of 5×5 m and 6×6 m, the ore yield per 1 m of blasthole in the proposed technology of breaking is greater than in the reference technology, and it is much lower in case of the other drilling patterns.

Processing of the data of the experimental blasting resulted in the dependence of rock mass yield on the blasthole pattern in the reference and proposed technologies of rock mass breaking (**Fig. 6**).

It is worth noting that the yield of oversize varies from 0.8% to 2.7% in the basic technology and from 0.6% to 1.9% in the proposed technology.

Table 1. Comparison of blasting results

Blast No.	Rock volume, m^3	Drilling pattern	Average length of blastholes, m	Number of blastholes	Total drilling length, m	Explosive consumption, kg	Powder factor, kg/m^3	Oversize yield, %
Reference blasting								
1	6 420	4×4	9.27	49	454.3	7 632.24	1.19	0.8
2	21 100	4.5×4.5	17.1	80	1 352.7	22 725.36	1.08	1.1
3	8 730	5×5	10.84	47	509.4	7 886.97	0.9	2.4
4	14 222	5.5×5.5	14.1	58	817.3	13 730.64	0,97	2.5
5	18 860	6×6	12.4	68	843.3	13 188.42	0.7	2.7
Experimental blasting								
1	3 372	4×4	5.1	60	305.8	4 588.11	1.36	0.6
2	10 701	4.5×4.5	10.67	70	747.2	11 205.24	1.05	0.8
3	7 134	5×5	8.65	48	415.2	6 397.9	0.9	1.9
4	7 980	5.5×5.5	10.02	54	541.2	8 572.19	1.07	0.95
5	22 140	6×6	12.7	89	1 129.6	17 671.79	0.8	1.1

Conclusions

The research and the data processing have resulted in the following conclusions:

1. The technology of rock mass prestressing is proposed to improve the quality of rock fragmentation by blasting. The technology includes drilling of additional blastholes and providing their explosion yield to be lower than the breaking point of rocks. The burden of the blastholes is determined for each case individually, considering both geological conditions of the deposit and crushing zone radii. The distance to the additional row of blastholes and the distance between the blastholes are selected based on the burden of the first additional row of blastholes, and all primary blastholes must be equally spaced from the additional blastholes.

2. The second experimental blast yielded the best economic parameters with the oversize yield of 0.8% and the

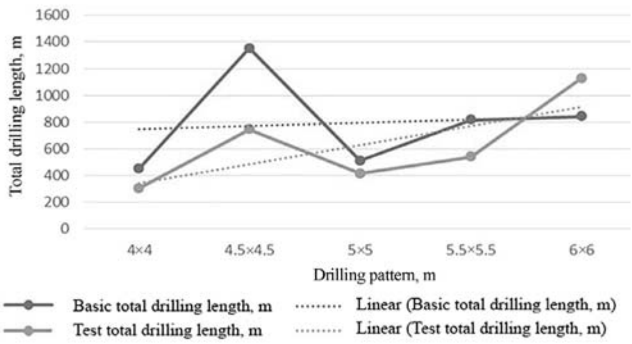


Fig. 4. Total drilling length versus drilling pattern in reference and proposed technologies of rock breaking

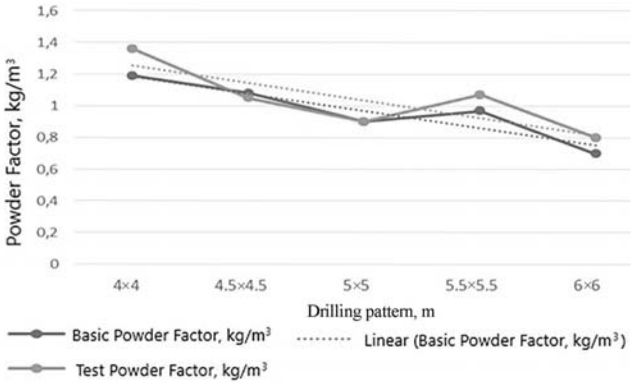


Fig. 5. Powder factor versus drilling pattern in reference and proposed technologies of rock breaking

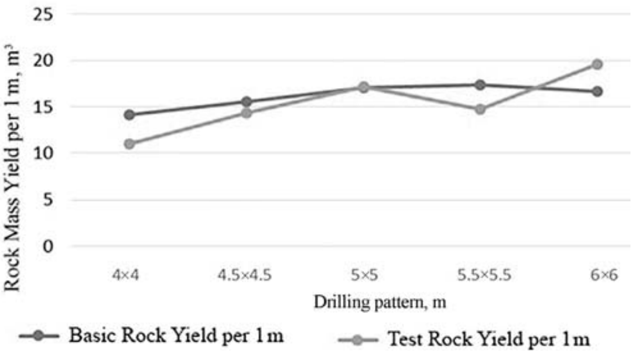


Fig. 6. Rock mass yield per 1 m versus drilling pattern in reference and proposed technologies of rock breaking

Table 2. Comparison of ore yields per 1 m of blastholes

No.	Drilling pattern, m	Ore yield per 1 m of blasthole, m^3/m	
		Reference blasting	Experimental blasting
1	4×4	14.1	11.03
2	4.5×4.5	15.6	14.3
3	5×5	17.1	17.2
4	5.5×5.5	17.4	14.7
5	6×6	16.7	19.6

powder factor of 1.05 kg/m^3. Moreover, the proposed technology resulted in a 10% increase in the rock excavation rate.

3. The total drilling length in the experimental blasting in the test block, with the expanded drilling pattern and additional blastholes was 747.20 m. With the regular drilling pattern used in the same conditions, the total drilling length can be 749 m. Thus, the drilling cost of the new technology is the same.

4. The powder factor in the experimental blasting in the test block with the expanded drilling pattern and additional blastholes was 11 205.24 kg. With the regular drilling pattern used under similar conditions, the powder factor is 12 145.35 kg. Savings of explosives are 7.74% due to the expansion of the drilling pattern to 4.5×4.5 m and owing to the reduction of the mass of charge in the experimental blastholes by 30%.

Acknowledgment

The authors would like to express their gratitude to the Committee on Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan for providing grant No. AP14871011, which made this research possible. The authors would also like to thank all the participants and contributors to this study for their valuable input and cooperation.

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