The Influence of Parameters of Drilling and Blasting Operations on the Performance of Hydraulic Backhoes at Coal Open Pits in Kuzbass

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The article describes a problem of increasing hydraulic backhoes performance on the open coal pits depending on the parameters of drilling and blasting operations. When developing coal-bearing zones of complex-structured coal deposits, due to the design features of working equipment, mobility and autonomy, hydraulic backhoe excavators are able to perform both mining and overburden operations more efficiently than rope shovels. Hydraulic backhoe excavators are extracting machines with downward scooping, which determines the working out of shotpile of the blasted rock in several layers. Therefore, the primary technological directions of increasing the efficiency of backhoes' operations are the justification of parameters of drilling and blasting operations to ensure a rational degree of rock crushing and rational parameters of the face for maximum realisation of the design features of excavators. As a result of research, the specific consumption of explosive and the diameter of explosive boreholes are among the most significant controlled technological factors that affect the quality of rock crushing. The substantiation and practical application of rational technological parameters for hydraulic backhoes at the open coal pits can provide higher technical and economic indicators on the backhoes application, compared to the rope shovels. The research was based on the data from Kuzbass (Kemerovo region, Russia) coal deposits being developed by open pits.

Keywords: *drilling and blasting operations, the performance of backhoes, the diameter of boreholes, specific consumption of explosive, excavators*

Introduction

More than 110 excavators of hydraulic backhoe type with a bucket capacity of more than 5 m^3 are currently in operation at Russian open-pit mines at overburden operations (Kolesnikov et al., 2018). About 60 machines of this type operate in the open-pit mining of Kuzbass coal deposits. In particular, at the open-pit mines of coal company "Kuzbassrazrezugol", the number of overburden mining and transport complexes based on hydraulic backhoes (produced by Liebherr, Caterpillar, Terex, Hitachi) with a geometric bucket capacity of more than 5 m^3 was about 20 or 12% of the total excavators' pool at the end of 2011. During 2015, they have excavated and loaded more than 100 million m^3 of the rock mass (Tyulenev et al., 2019). Over the coming years, the number of excavators of hydraulic backhoe type is expected to significantly increase and bring the annual volume of work with their use to 150 million m^3 of the rock mass. The average bucket capacity will be more than 14 m^3.

At the initial stage of implementation at Kuzbass open-pit mines, the performance of backhoes for stripping work was significantly less than the productivity declared by the manufacturers. This was explained not only by the lack of practical experience in operating hydraulic backhoes, but also by the lack of recommendations on the basis of which it would be possible to create the most favorable conditions for the realisation of the high potential of backhoe-type excavators (only a few researches in this area were performed) (Bhaveshkumar and Prajapati, 2013; Prakash et al., 2013; Nam and Drebenstedt, 2004; Nam and Drebenstedt, 2009; Conigliaro et al., 2009; Moore and Paredis, 2010; Zhang et al., 2011).

The functional dependence of the performance of the excavator on the parameters of drilling and blasting operations is a necessary element of the optimisation model for substantiating its rational value (Hrehová et al., 2012; Mattis et al., 2012). There are various methods of establishing the dependence of the performance of an excavator on the parameters of drilling and blasting operations, differing in the detail of taking into account the initial factors. For example, the excavator's performance is calculated depending on the diameter of the middle piece of the blasted rock mass and the associated excavation parameters (rock loosening coefficient, bucket filling ratio, duration of individual operations of the excavator's production cycle) (Matushenko, 1975; Litvin and Nikiforova, 2008). Along with this, there is a less detailed approach, in which only the average diameter of the rock piece, the coefficient of rock loosening in the shotpile and the share of the oversized fraction are involved in the calculation (Alabuzhev et al., 1966; Molotilov et al., 2009). The use of a particular approach determines the range of factors that can be researched using an appropriate calculation model and, therefore, has the defined purpose.

Therefore, the challenge remains to justify the dependence of the excavator's performance on the parameters of drilling and blasting operations based on the specific consumption of explosive, which, in turn, is determined by the strength of the explosive rock, the diameter of the borehole charge, and the model of the excavator. Correct determination of specific consumption, in turn, can allow achieving the optimum degree of

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crushing of overburden, which is an essential factor determining the performance of excavators.

Passport excavator performance (Q_p, m^3 / hour) is set from the formula (1):

$$Q_p = \frac{3600 \times E}{t_{cp}} \tag{1}$$

where E is the geometric capacity of the excavator bucket, m^3;

t_{cp} is the passport cycle duration when rotated through an angle of 90°, sec.

The technical performance of the excavator (Q_t, m^3 / hour) depends on many factors, the main of which are the characteristics of the size and state of the exploded rock mass. In turn, the characteristics mentioned above of the quality of explosion preparation of the rock mass are determined by the combination of technological parameters and the strength properties of the rocks. These include:

- specific consumption of explosive (q);
- borehole diameter (d_w);
- the geometric capacity of the excavator bucket (E);
- coefficient of rock hardness by Protodyakonov (f).

The indicator of the efficiency of the excavation process is the ratio of the technical performance of the excavator in specific mining conditions to the passport performance (excavation efficiency coefficient, C_{ee}):

$$C_{ee} = \frac{Q_t}{Q_p} \tag{2}$$

The excavation efficiency coefficient has the following properties.

1. The efficiency coefficient is an asymptotically increasing function up to 1 according to the parameters of specific consumption of explosive and the capacity of the excavator bucket.
2. The efficiency coefficient is a decreasing function according to the parameters of the diameter of boreholes and the strength of rocks.
3. The partial derivatives of specific consumption and the capacity of excavator bucket with q = 0 and E = 0 are equal to zero.
4. The mathematical design of specific consumption of explosives, borehole diameter and rock strength in combination with the dimensional magnitude of the acceleration of gravity are the dimensionless value and characterises the ratio of the significance of these factors, which is experimentally confirmed by the overburden crushing model (Katsubin and Makridin, 2018). It should be borne in mind that the indicator of the rock hardness actually has the dimension of pressure.

On this basis, the functional dependence of the excavation efficiency coefficient C_{ee} is taken as an exponent (Litvin and Nikiforova, 2008):

$$C_{ee} = 1 - exp\left[-a \times \left(\frac{q}{d_w \times f}\right)^b \times E^c\right] \tag{3}$$

By mathematical transformations, the expression can be reduced to a linear model with three unknown parameters *a, b, c*, which were determined by multivariate analysis methods using actual data on 78 mass explosion projects at Kuzbass open pits in 2011-2015. These values were defined as the following: a = 840, b = 2, c = 0.5.

Materials and Methods

An important role in achieving the maximum performance of an excavator is played by the degree of crushing of rocks by an explosion. Imitation calculations confirmed that the rational degree of crushing depends mainly on the operational parameters of the excavator, the blockiness of the exploded rocks. The rational degree of crushing Z_r depending on these factors can be calculated by the formula (4) (Kovalev and Litvin, 2012):

$$Z_r = 1 + \frac{d_e^{n1}}{E^{n2} + n_3} \tag{4}$$

where d_e is the diameter of rock fracture without displacement, m (the distance between the adjacent cracks in the rock array);

n_1, n_2, n_3 are the constant parameters characteristic of the considered excavators (hydraulic backhoes), n_1 = 2.0, n_2 = 0.13, n_3 = 0.93.

The value of n_2 = 0.13 confirms the conclusion made when analysing the actual performance of hydraulic backhoes and their power characteristics that, as the bucket capacity increases, the rational degree of crushing changes to a lesser extent than when using old models of rope shovels (for rope shovels $n_2 = 0.9$).

The rational values of the specific consumption of explosive in the preparation of overburden for hydraulic backhoes are 20–50% higher than the values, recommended for rope shovels with a corresponding bucket capacity (Scott et al., 2010; Hummel, 2012). Herewith the actual values of specific consumption of explosive are higher than calculated ones by 10–30%. For comparison, Table 1 presents data on a rational degree of crushing for the rope shovels (ECG excavators) with a bucket capacity of 5–20 m^3 with the most common rock hardness ratio for Kuzbass open pits f = 5-9 (Tyulenev et al., 2017).

Table 1 – Rational degree of crushing for explosive rock preparation for basic models of rope shovels

The rock hardness ratio by Protodyakonov	***The geometric capacity of the excavator bucket, m^3***		
	5	***10***	***20***
5	*1.40*	*1.36*	*1.32*
6	*1.58*	*1.52*	*1.46*
7	*1.79*	*1.71*	*1.63*
8	*2.03*	*1.92*	*1.82*
9	*2.30*	*2.17*	*2.04*

According to Table 1, in the considered bucket capacity and rock hardness, the degree of crushing for hydraulic backhoes Z_r = 1.53-2.53, and for basic models of rope shovels Z_r = 1.40-2.04. At the same time, as the bucket capacity increases from 5 to 20 m^3, the degree of rock crushing for hydraulic backhoes decreases by 4-6%, and for rope shovels by 9-24%.

Hydraulic backhoes require a higher quality of explosive crushing of overburden, which predetermines the need to increase the specific consumption of explosives by 4–15% compared with the basic models of rope shovels with comparable bucket capacity (Table 2).

Table 2 – Rational degree of crushing of explosive rock preparation for hydraulic backhoes

The rock hardness ratio by Protodyakonov	***Backhoe model, the geometric capacity of the excavator bucket, m^3***						
	Liebherr-984C			***Liebherr-994***		***Liebherr-9350***	***Terex***
	5.2	*6*	*7.5*	*10.3*	*11*	*13.8*	*20.6*
3	*0.9*	*0.9*	*0.9*	*1.18*	*1.18*	*1.18*	*1.17*
4	*1.34*	*1.34*	*1.33*	*1.32*	*1.32*	*1.31*	*1.30*
5	*1.53*	*1.53*	*1.52*	*1.50*	*1.50*	*1.49*	*1.47*
6	*1.77*	*1.76*	*1.74*	*1.72*	*1.72*	*1.70*	*1.68*
7	*2.04*	*2.03*	*2.01*	*1.98*	*1.98*	*1.96*	*1.92*
8	*2.36*	*2.35*	*2.32*	*2.28*	*2.28*	*2.25*	*2.21*
9	*2.72*	*2.70*	*2.67*	*2.62*	*2.62*	*2.58*	*2.53*
10	*3.13*	*3.10*	*3.06*	*3.01*	*2.99*	*2.95*	*2.89*
11	*3.58*	*3.54*	*3.50*	*3.43*	*3.41*	*3.36*	*3.28*
12	*4.07*	*4.03*	*3.97*	*3.89*	*3.87*	*3.81*	*3.71*

According to Table 2, the rational degree of crushing for the rock with higher Protodyakonov hardness ratio for hydraulic backhoes is 15-25% higher than for rope shovels. Compared to the same dependence for increasing the bucket capacity for both types of the excavators, it confirms the fact that hydraulic backhoes are the excavation equipment that is very sensitive to the quality and uniformity of explosive crushing of rock. It is known that the diameter of boreholes is a parameter of drilling and blasting operations, which significantly affects the quality of explosive preparation of the rock mass. Therefore, the justification of the model of drilling rigs, working in complex with hydraulic backhoes should be made taking into account the technical indicators of the drilling, blasting and loading operations.

In the theory and practice of explosive preparation of overburden to excavating and loading operations, there is a fundamental principle – more even distribution of explosive in the rock array contributes to improving the quality and uniformity of rock crushing. From this point of view, the use of explosive boreholes of smaller diameter has a more favourable effect on the quality and uniformity of crushing of the exploded rock mass.

At the same time, at present, at Kuzbass coal open pits, there is a steady tendency to increase the volume of drilling of explosive using drilling rigs with relatively large diameter boreholes (more than 240 mm). The reason for this is considered to be the higher performance of powerful drilling rigs both in the total length of the boreholes and in the volume of drilled rock. Over the past 10 years, the average diameter of blast holes has increased by more than 15% (Fig. 1).

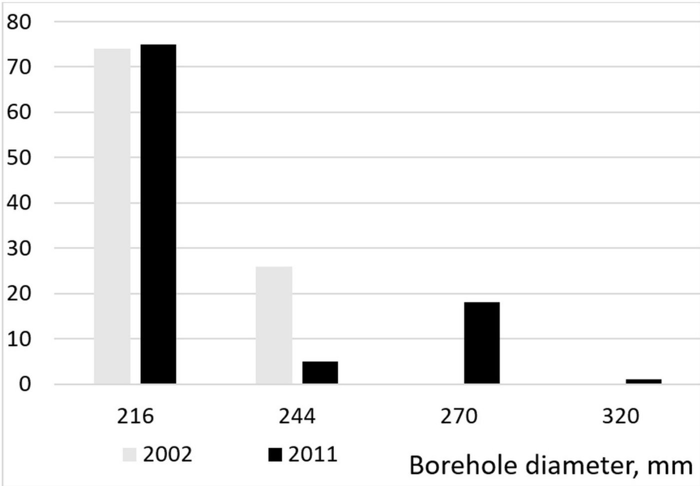

Fig. 1. Dynamics of drilling borehole diameter (the share in all boreholes – based upon the data from authors' surveys and calculations).

As can be seen in Fig. 1, by 2011, up to 20% of the boreholes at Kuzbass open pits had the diameter of 270-320 mm, while in 2002 there were none of them. The increase in the diameter of the boreholes entails an increase in the specific consumption of explosives. In addition, there is a need to increase the over-drill as a part of the borehole (Fig. 2). Over-drilling of boreholes is carried out with the purpose of developing the bench floor, which ensures the possibility of maintaining the horizontal level of the lower working platform. Low quality of the rock mass preparation at the bench floor is due to the low loosening rate of the array in this zone. The possibility of increasing the loosening rate at the floor level is possible, in particular, by increasing the length of the over-drill (l_{over}). It also means an increase in tamping length (l_{tamp}).

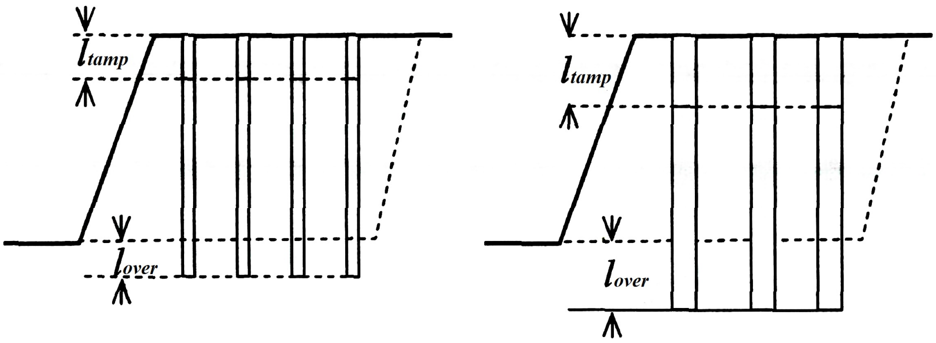

Fig. 2. Conventional charge pattern at different borehole diameters (source: own processing).

The diameter of the boreholes determines the uniform distribution of the total amount of explosives in the exploding rock array (Chung et al., 1991; Benselhoub et al., 2019). With the existing principles for calculating the tamping of boreholes, it is known that a more uniform distribution of explosives in the array corresponds to smaller values of the diameter of the boreholes (Wu et al., 2006; Sun and Deng, 2014; Wang et al., 2018).

Practical experience, experimental and theoretical studies indicate that the uniformity of placement of explosives in the array, achieved by reducing the diameter of the boreholes, contributes to increasing the uniformity and degree of crushing of the rock mass (Litvin and Nikiforova, 2008; Kovalev and Litvin, 2012). This fact applies to all categories of overburden and all types of explosives used at Kuzbass open pits. For illustration in Fig. 3, the qualitative influence of the diameter of the charge on the output of the oversized fraction of blasted rocks of various categories by explosiveness is shown.

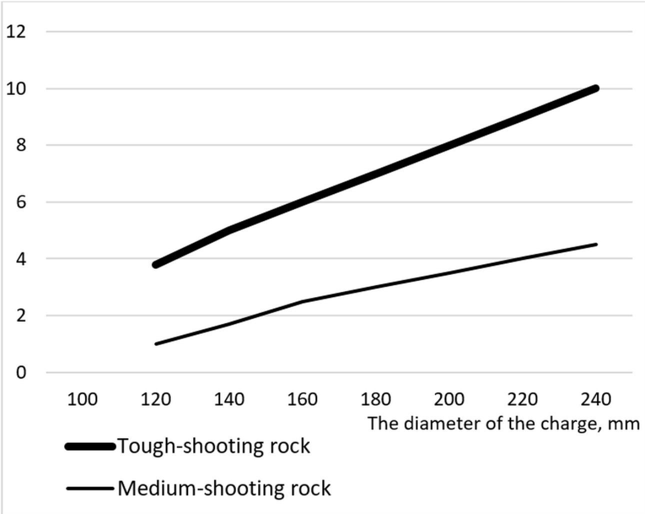

Fig. 3. Influence of charge diameter on the output of oversized fractions for hard and medium shooting rocks (based upon the data from authors' surveys and calculations), %.

As it can be seen in Fig. 3, the lower borehole diameter provides higher blasting quality both for tough-shooting and medium- tough- shooting rocks. The effect of charge diameter on the quality of crushing at different specific consumption of explosives manifests itself with different intensity, and in order to maintain the degree of crushing at a certain level with increasing borehole charge diameter, it is necessary to increase the specific consumption of explosive.

So far, in the methodological part of the standard projects of mass overburden rocks explosions in Kuzbass, the following recommendations were made for the use of boreholes of different diameters drilled by rigs developed for rope shovels in 1980-1990s (Oparin et al., 2012):

1. For easily shooting rocks of homogeneous blockiness, it is possible to use boreholes of relatively large boreholes diameter (250 - 350 mm).
2. For middle-shooting rock category, borehole diameters up to 250 mm are preferred.
3. For tough- shooting rocks that are not uniform in blockiness, the most appropriate are relatively small diameters (150-190 mm).

However, currently, there are no sound recommendations on the choice of the size of modern high-performance diesel drilling machines, working complete with hydraulic backhoes.

The increase in the specific consumption of explosives with an increase in the diameter of the boreholes is due to the existence of two regularities. The first is related to the need to ensure a rational degree of rock crushing for the applicable size of the excavator's bucket. This pattern is reflected in the previously established and statistically justified formula (3) (Litvin et al., 2009), which is the basis for calculating rational values of the specific consumption of explosives in the development of projects for mass explosions at many Kuzbass open pits.

The second regularity is that as the borehole diameter increases, it becomes necessary to increase borehole over-drill in order to maintain high-quality explosive development of the bench floor. In the methodological recommendations made for Kuzbass open pits, the length of the over-drilling of boreholes is related to their diameter in accordance with the formula (5):

$$l_{over} = 3d_w \times d_e + 1 \tag{5}$$

where d_w is borehole diameter, m;

d_e is the diameter of rock fracture without displacement, m

As the diameter of boreholes increases, not only the design specific consumption of explosives increases but also the actual specific consumption – the ratio of the mass of the charge in the borehole to the rock volume, bounded by the dimensions of borehole grid and the depth of borehole (not including over-drilling). Fig. 4 shows the calculated dependences of the design and specific consumption of explosives on the borehole diameter.

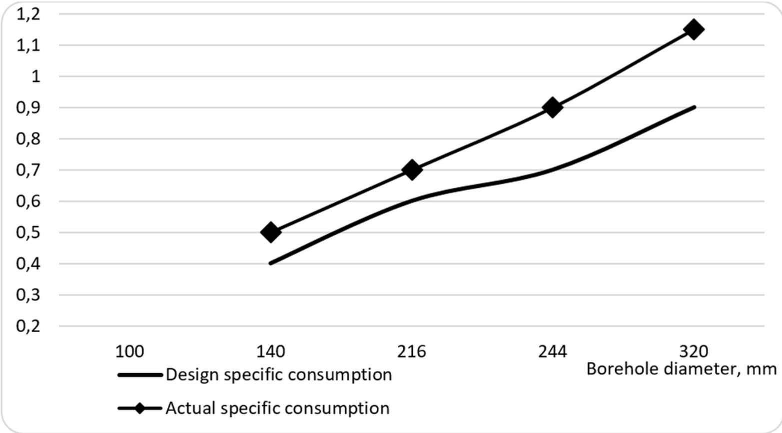

Fig. 4. The characteristic dependence of the specific consumption of explosives on the diameter of boreholes, kg / m³ (based upon the data from authors' surveys and calculations).

As can be seen in Fig. 4, both the design and actual specific consumption, providing the necessary degree of fragmentation, increase almost in proportion to the increase in the diameter of boreholes. It fully corresponds to the dependence shown in Fig. 3 (decrease in oversized fractions output with lowering the diameter of the boreholes).

Results

Regularities of changes in the specific consumption of explosives (Fig.4), the productivity of drilling machines depending on the diameter of boreholes, and the correspondence with the cost parameters of drilling and blasting allowed us to establish the pattern of its influence on the excavators' productivity.

The output of the rock mass can be calculated as:

$$v = \frac{P \times k_{fw}}{q} \tag{6}$$

where: p is the capacity of 1 m borehole, kg;
k_{fw} is the fill factor of the borehole 0.7 - 0.75);
q is the specific consumption of explosives, kg / m^3.

The capacity of 1 m borehole is defined as:

$$P = \frac{\pi d_w^2}{4} \times \rho \tag{7}$$

where ρ is the bulk density of explosives, kg / m^3.
The output of oversized fractions (φ) is set from the following expressions:

$$\varphi = exp(-0.8\lambda^{2.5}) \tag{8}$$

$$\lambda = \frac{l_N}{d_{av}} \tag{9}$$

$$l_N = 0.8E^{0.33} \tag{10}$$

where l_N is the average diameter of an oversized piece of the rock mass (along with an excavator bucket), m;
d_{av} is the diameter of the middle piece of the blasted rock mass, m;
E is the excavator bucket capacity, m^3.
The diameter of the middle piece of the blasted rock mass is determined by the formula (11):

$$d_{av} = \frac{5d_w \times d_e}{5d_w + q \times d_e} \tag{11}$$

The behaviour of the excavation efficiency coefficient C_{ee} and Technical performance of the hydraulic backhoe excavator (Q_t,) during the excavation of blasted rock was researched for the following conditions for drilling, blasting and excavation works:

- overburden rocks have the hardness ratio by Protodyakonov of 3-12;
- the drilling of rocks is made by boreholes with a diameter d_w = 0.216 m;
- regulation of the width of shotpile was carried out by the schemes of millisecond-delay blasting and with the use of explosions with a retaining wall;
- the specific consumption of explosives has its own range of changes depending on the category of rocks by blockiness (Markov et al., 2018) (Table 3).

Table 3 – Range of specific consumption of explosives

Indicators	***Category of rocks by blockiness (the distance between the adjacent cracks in the array, m)***				
	I (<0.1)	***II (0.1-0.5)***	***III (0.5-1.0)***	***IV (1.0-1.5)***	***V (>1.5)***
The lowest value of specific consumption of explosive, kg / m^3	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*
The biggest value of specific consumption of explosive, kg / m^3	*0.5*	*0.8*	*1.0*	*1.2*	*1.4*

A comparative assessment of the actual (really achieved) and estimated technical performance of hydraulic backhoes Q_t is given in Table 4. The reliability of the approximation of technical performance is 85%.

Table 4 – Comparative evaluation of the calculated and actual performance of the excavator (based upon the data from authors' surveys and calculations)

Bucket Geometric Capacity E, m^3	***The rock hardness ratio by Protodyakonov (f)***	***Specific consumption of explosives (q), kg / m^3***	***The technical performance of the excavator, m^3 / hour***	
			Actual	***Estimated***
5.2	*5*	*0.48*	*307*	*310*
6.0	*9*	*0.82*	*342*	*282*
7.5	*9*	*0.75*	*301*	*337*
10.3	*5*	*0.45*	*496*	*531*
11.0	*9*	*0.75*	*420*	*474*
	10	*0.66*	*499*	*430*
	11	*0.71*	*490*	*432*
	12	*0.8*	*533*	*444*
13.8	*5*	*0.41*	*607*	*700*
20.6	*5*	*0.29*	*842*	*901*
	6	*0.55*	*835*	*930*
	9	*0.75*	*791*	*870*
	10	*0.71*	*971*	*926*

Table 4 data analysis allows concluding that the discrepancy between actual and estimated data does not exceed 17% with an average value of 11%. The specific consumption of explosive is one of the most significant factors that affect the drilling and blasting preparation of rocks for excavation. The substantiation of the specific consumption of explosives is carried out taking into account the influence of the rock hardness (Fig. 5), as well as some other mining engineering factors.

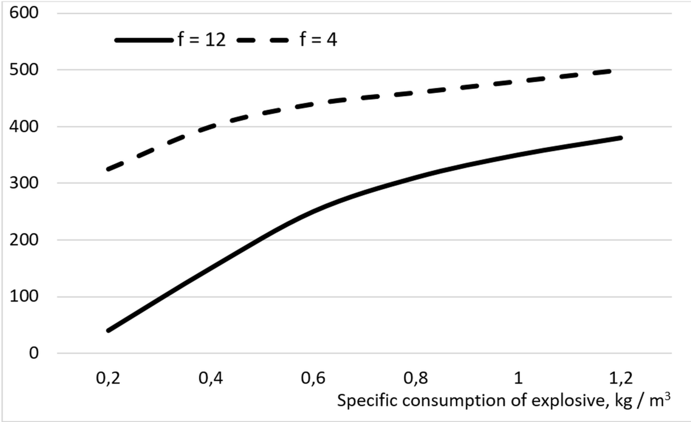

Fig. 5. Characteristic dependence of the passport excavator performance (m^3 / hour) on the specific consumption of explosives (based upon the data from authors' surveys and calculations).

As can be seen in Fig. 4, the growth of specific consumption of explosives influences on the backhoe performance in the maximum extent in the interval of 0.2-0.7 kg / m^3. It is true for both values of Protodyakonov rock hardness ratio f = 4 (sandstone of middle hardness) and f = 12 (very hard sandstone, siliceous schist). The following growth of specific consumption of explosives (0.8-1.2 kg / m^3) leads to a slight increase in backhoe productivity. This can be explained by the growth of borehole diameter, which causes the expanding of the boreholes grid and worsening the rock crush.

Discussion

Hydraulic backhoes – the excavators that actively replace rope shovels at Kuzbass open pits, are more depending on the quality of explosive preparation of rock mass, since the specific force on the cutting edge of the bucket of hydraulic excavators is 1.5-2.0 times less, and the force applied to 1 ton of rock is 3-4 times more compared with rope shovels. This makes hydraulic backhoes more productive machines, but their performance greatly depends on the accuracy of drilling and blasting parameters defining. So they require a higher quality of crushing of the blasted rock mass, which is less dependent on the model of the excavator as compared with rock shovels with comparable bucket capacity.

At present, there is no uniform regulatory framework for explosive consumption for various types of excavators in Kuzbass. Thus, for hydraulic backhoes Liebherr-994, Liebherr-9350, Terex (with a bucket capacity of 10.3-20.6 m^3) and the overburden rocks of the II^{nd} blockiness category, the specific explosives consumption is 0.45-0.6 kg / m^3. At the same time, for a Liebherr-984C excavator in close conditions, the specific consumption is 0.45-0.52 kg / m^3. Reducing the borehole diameter makes it possible to reduce the specific consumption of explosives due to a more even distribution of explosives in the array and a shorter over-drilling length relative to the bench floor. However, there is a decrease in the productivity of drilling equipment both along the length of the drilled boreholes and in the volume drilled. On the other hand, an increase in the borehole diameter is associated with the need for an almost proportional increase in the specific consumption of explosives.

The expedient diameter of borehole charges in the preparation of overburden for excavation by hydraulic backhoes with a bucket geometrical capacity from 5 to 22 m^3 for small, medium and large blocks of overburden is respectively 170-240 mm, 170-220 mm and 170-190 mm.

Specific consumption of explosives, achieved on the basis of production experience of Kuzbass open pits, are characterised by significant fluctuations with a scope of this indicator reaching 1.5-2.33 times. For example, several explosions for a Liebherr-984C backhoe extracting the overburden rocks with Protodyakonov hardness ratio of 5 differ in specific consumption of explosives in 1.52 times. The explosions in the rock face for Liebherr-9350 backhoe, according to the rocks with Protodyakonov hardness of 5-6 differ in specific consumption of explosives in 1.74- 2.33 times. The wide scope of specific consumption of explosives, obtained for different blasts, allowed maintaining the constant backhoe productivity with the dispersion of values not less than 18%.

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