The process of destruction of rock by an explosion with the use of blasthole stemming in roadheading mining operation

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Abstract. Blasting is one of the main methods of rock destruction and accounts for approximately 20% of the cost of mining operations. Given that the efficiency of the explosion for crushing does not exceed a few percent, it becomes obvious that further improvement of explosive destruction is necessary, taking into account the new achievements of science and technology. One of the main ways to improve the efficiency of underground mining is to improve the conduct of drilling and blasting operations with the use of the stemming plays a significant positive role in the operation of the explosion.

1. Introduction
The effectiveness of explosive destruction of rocks with the use of stemming is justified by many researchers in their works [1-15].

The use of a stemming in the explosive destruction of rocks prevents energy losses during the detonation of the explosive charge, ensuring greater completeness of its detonation and the release of the maximum value of its potential energy, increases the effective length of the blast wave of the explosion and the initial pressure of the explosion gases, increases the duration of the piston action of the detonation products on the walls of the charging cavity and the length of radial cracks formed during explosions of charges [16-18].

Long-term practice of blasting during underground mining operations, as well as special experimental and analytical studies indicate that with a good quality of the stemming material and sufficient length, the stemming is so compacted in the holes that the resulting friction exceeds the ejection effect of the detonation products. Such a stemming forms a dense wedge in the hole, which does not fly out of the hole, but moves along with the destroyed array [14].

2. Method
Analyzing the current state of the issue of the mechanism of explosive destruction of a rock massif, the authors [19, 20] note that forces of various physical nature participate in the destruction of the massif by an explosion. But, despite this, the quantitative description of the process is based on a single destructive force or a complex-generalized indicator. The scheme of interaction of various forces when a concentrated charge or an elongated charge explodes in the plane that secures the charge perpendicular to its length at any point is shown in Figure 1.

In this case, the purpose of the stemming is to create resistance to the explosion products in the most weakened place of the exploding medium, in order to ensure the effective use of the explosion energy. The amount of resistance of the face depends on its size and characteristics of the stemming material. Stemming materials can be loose, liquid, plastic, solid or technological. Bulk stemmings are used in descending charges. The bulk density of such stemmings depends on the...
characteristics of the stemming materials and is in the range of 1.2-1.5 t/m³. Liquid stemmings are represented by water or gel compositions. Such stemmings are used in descending charging cavities or in shells in charges up to the horizontal direction. The density of such stemmings is within 1 t/m³ or slightly more.

Plastic stemmings of several components (the most well-known is sand - clay mixture) have a density of 1.5-2.0 t/m³, higher resistance in the mass of the stemming and along the walls of the charging cavity. The greatest resistance is created by the stemmings of fast-hardening binders with a density of 2 t/m³, a large internal resistance and resistance along the walls of the charging cavity. Technological stemmings understood as a technique when the charging cavity has a cross-section less than the diameter of the charge.

Figure 1. Diagram of interaction of forces during explosive charge explosion: 1-total pressure of explosion products; 2-static pressure of explosion products (EP), kgc/cm²; 3-dynamic pressure of EP, kgc/cm²; 4-residual dynamic pressure, kgc/cm²; 5-axis of the explosion funnel; 6-naked plane; 7-boundary of the explosion funnel; 8-shock waves; 9-charge of explosives; 10-peak load of static pressure; H-depth of laying of the explosive charges, m.

The main compaction of the stemming material occurs at the initial moment of explosion development due to the impact of shock waves and piston pressure on the face of the detonation products. As a result of this compaction on the contact of the face with the walls of the hole there are forces of lateral expansion. The process of ejecting the stemming from the hole can be represented as follows. Since the beginning of the detonation of the explosive charge, the gaseous products of detonation, acting on the end of the face, tend to move it. Until there is a shift, the resistance to the ejecting action of the detonation products is due to the inertia of the rest of the own mass of the face, the forces of internal friction and adhesion of the particles of the stemming material. But immediately after compaction of the latter, there is a shift of the face and in the future its movement is prevented only by weight and internal friction forces. The diagram of the forces acting on the stemming during the explosion of the blasthole stemming is shown in Figure 2.

Figure 2. The scheme of the forces acting on the stemming from plastic or granular materials during the explosion: σδ — lateral pressure forces; τ — displacement resistance of the stemming material; G — weight of the stemming; P — average pressure of gaseous detonation products.

The existence of optimal values stemming from the point of view of obtaining maximum explosion effect is confirmed by experimental researches of the author [15], who found that the yield of the coarse fraction with increasing length of stemming to a certain value decreases, then remains practically unchanged. On
the contrary, the yield of small fractions increases with the length of the stemming. All this once again confirms that in each particular case, there is an optimal value of the stemming, which provides the maximum possible explosion effect, all other things being equal.

The minimum length of the locking face, i.e., such that a solid wedge is formed that does not fly out of the hole, can be determined from the condition that the total resistance of the friction forces on the shear surface of the stemming should be greater than or at least equal to the ejection effect of the detonation products

$$\Sigma Q_{\text{tr}} \geq S,$$  

(1)

where $Q_{\text{tr}}$ is the total resistance of the friction forces on the shear surface of the stemming, kg;

$S$ – the ejection force of the detonation products, kg.

The left side of inequality (1) can be represented as an expression

$$\Sigma Q_{\text{tr}} = \pi d l \tau_{\text{tr}},$$  

(2)

where $d$- hole diameter, m;

$l_{\text{tr}}$ - length of the stemming, m;

$\tau_{\text{tr}}$- the intensity of the internal friction forces of the stemming material compacted in explosion, kg/m².

The ejection force of the detonation products $S$ in the case of an application of plastic (clay or sand-clay) stemming, when the face mass completely covers the cross section of the drill hole and the face of the stemming directly adjacent to the charge can be considered as a solid piston, will be

$$S_{\text{pl}} = \left(\pi d^2/4\right)P,$$  

(3)

where $P$- the average pressure of the detonation products in the hole, kg/m².

When the stemming is made of granular materials with a certain porosity, the force $S$ that ejects the stemming out will be less, since the face of the stemming will perceive the pressure of the detonation products not as a solid piston, but as a piston with holes.

Therefore, the force of the detonation products, ejecting out of the drill hole stemming of granular materials, is determined by the expression:

$$S_{\text{st}} = \left(\pi d^2/4\right)P(1-K_p),$$  

(4)

where $K_p$- porosity coefficient of the grained stemming material. For sand with medium strength $K_p = 0.3-0.4$.

Then taking into account the expressions (2), (3), (4) the inequality (1) for plastic and granular stemming materials can be represented as follows

$$l_{\text{tr}} \geq Pd/4,$$  

(5)

$$l_{\text{tr}} \geq (Pd/4)(1-K_p),$$  

(6)

From the expressions (5) and (6) it is not difficult to determine the minimum length of the locking hole of the non-flying plug. However, experimental studies of the authors [3] indicate that a certain part of the stemming adjacent directly to the hole mouth, after 0.4—0.5 ms from the moment of the charge detonation, is torn off and under the influence of reflected shock waves is ejected from the hole. Therefore, when determining the minimum length of the stemming that forms a non-flying plug in the hole, expressions (5) and (6) must be corrected to take into account the detached part of the stemming material.

As a result, the following expressions can be obtained for determining the length of a plastic and grained stemming, respectively:

$$l_{\text{pl}} \geq Pd/4\tau_{\text{tr}} + l_{\text{tr,off}},$$  

(7)

$$l_{\text{st}} \geq (Pd/4)(1-K_p) + l_{\text{tr,off}},$$  

(8)

where $l_{\text{pl}}$ - the length of the stemming, at which a non-flying plug is formed, in the case of using plastic stemming materials, m;
According to the authors [14], who studied the nature of the discharge from the hole stemmings of various types, it was found that the value of $l_{z,sep}$ for both plastic and granular materials is 20-40 cm. The calculation made according to formulas (7) and (8) shows that a plastic stemming, depending on the content of sand and clay, forms a plug that does not fly out of the drill hole at a length of 1.8-2.0 m. A plug of the same strength is formed at a length of 0.8-1.0 m in the case of using granular stemming materials. However, it is not possible to recommend formulas (7) and (8) for calculating the size of the hole stemming, since according to modern ideas about the mechanism of explosive destruction of rocks and the role of the internal stemming in this process, the use of an excessively long stemming, which remains stationary in the hole during the massif destruction, cannot provide optimal conditions for maximum use of the explosion energy.

To determine the rational length of the stemming it is advisable to use the formulated conditions for maximum use of the explosion energy the expressions of which are given below:

For direct initiation

$$v_z l_z = v_z (v_z t_p + l_{an})$$  \hspace{1cm} (9)

For inverse initiation

$$v_z l_z = v_z (v_z t_p - l_{an})$$  \hspace{1cm} (10)

Where $v_z$ - the velocity of detonation of explosives in the charge, m/sec, the velocity of detonation of explosives in the charge is determined by the type of explosive used and in each case is a known value.

$v_z$ - the ejection rate of stemming from the hole, m/sec;

$t_p$ - time of separation and displacement of rocks, sec. According to MakNII [8], with a length of about 2 m $t_p$ has the following values: in sandstones with one free face surface 4.3-10 msec, in the same rocks with two free face surfaces 0.2-12 msec; in clay shales with one free face surface 6-58 msec; in the same rocks with two free face surfaces 3-27 msec; in coal faces with one free face 9-33 msec.

$l_{an}$ - the length of explosive charge, m. The length of the explosive charge is set based on the number of holes and the value of the specific consumption of explosives, which is calculated using known formulas or accepted on the basis of practical data.

By combining the expressions (9) and (10) and substituting the values of the ejection rate of stemming into the resulting equation, we can obtain the formula [5] for determining the rational length of stemming for both direct and inverse charge initiation.

$$l_z = \beta \sqrt{(Pd(t_p \pm l_{an})) / (v_z^2 \gamma_z)}$$  \hspace{1cm} (11)

The plus sign in the expression under the cubic root refers to the case of direct initiation of charges, minus the inverse.

The value of the coefficient $\beta$ is determined experimentally and is equal to: for a stemming made of plastic materials 0.47, for a stemming made of granular materials 0.54.

$\gamma_z$ - the density of the stemming material, kg/m³.

3. **Results and Discussions**

Special study found that the amount of resistance per unit area of the cross-section of the face of the same length, but made of different materials, varies widely (Figure 3).
Figure 1. Graph of the dependence of the resistance of stemming on its length for various materials. 1-sand with a 50-mm plastic plug; 2-dry shale fines; 3-a mixture of lime fines with sand; 4-lime dust; 5-wet sand; 6-sand-clay mixture at a humidity of 7%; 7-a mixture of lime crumbs with sand; 8-clay at a humidity of 7%; 9-sand-clay mixture at a humidity of 12%; 10-clay at a humidity of 16%

Experimental explosions carried out in pure homogeneous rock salt at the Mariagluk mine (Germany) [22], showed that the limit line of least resistance when using a stemming is higher than in the case of exploding charges without a stemming (Figure 4).

Figure 4. Graph of changes of limit line of least resistance during explosion: 1-without a stemming; 2-with a stemming of 600 g of sand. Initiation from the hole mouth

Studying the influence of the conditions of blasting of borehole charges on the parameters of shock waves [23] found that when using a stemming, the energy of stress waves is greater than when blasting the same charges without a stemming. This is evidenced by the data, given in table 1, which shows that the maximum stress in the shock wave front in the case of using a stemming from a chip is almost 1.5 times higher than when blasting without a stemming.
Table 1. Impact of the type of stemming on the conditions of exploding charges

| The conditions of exploding charges | Maximum voltage in the shock wave front, MPa | Duration of the shock wave, ms | The length of the shock wave, m | Specific impulse, N/cm² | Energy flow density, N m/m² |
|------------------------------------|---------------------------------------------|-------------------------------|-------------------------------|-------------------------|--------------------------|
| Without a stemming                | 2.25                                        | 1500                          | 6.25                          | 1850                    | 12000                    |
| Stemming from water               | 3.12                                        | 1130                          | 5.87                          | 2450                    | 26000                    |
| Stemming from a chip              | 3.33                                        | 1610                          | 8.35                          | 2650                    | 33000                    |

Long-term practice of blasting shows that when blasting column (hole and blast-hole) charges, unsatisfactory crushing of the array is most often observed in the upper part of the charging chamber that is not filled with explosives. This phenomenon is explained by the author [9] as an uneven distribution of specific impulses along the side surface of holes or blast-holes. The graphs he built (Figure 3) indicates that the greatest value of the specific impulse is in the area of the charge location and significantly decreases as it moves away from it to the mouth of the charging chamber. The uneven distribution of pulses along the holes or blast-holes explains the uneven crushing of the massif.

Figure 3. Scheme of the distribution of specific pulses along the axis of the column charging chamber (according to F. A. Baum): 1 - with a stemming; 2 - without a stemming.

4. Conclusions

Without a deep understanding and consideration of the features of the processes occurring in the environment destroyed by explosives, it is impossible to properly design the work and, consequently, obtain the proper effect from their conduct. Therefore, the role of the stemming in the process of rock destruction should be considered in close relationship with the explosion mechanism itself and primarily with the impact of static pressure on the destroyed massif of detonation products and shock waves. At the same time, it is necessary to take into account the nature of the destroyed rocks.

The analysis of theoretical and experimental studies carried out over the past decades [1-15] shows that the complex of effects on the rock mass can only be achieved by simultaneously using a strong stemming that locks the explosion products in the charging cavity until the destruction of the exploding environment. All this allows us to conclude that the optimal from the point of view of the explosion efficiency should be recognized as such a stemming, which in the process of explosive destruction of the massif will ensure the sealing of the charging cavity for the time necessary for the separation and destruction of rocks in the direction of line of least resistance.
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