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# Determining the performance of explosives for blasting management

**Maksym Kononenko[1], Oleh Khomenko[2], Ihor Kovalenko[3], Andrii Kosenko[4], Roman Zahorodnii[5], Roman Dychkovskyi[6]**

*[1]Dnipro University of Technology, Department of Transport systems and energy-mechanical complexes, Yavornytskoho Ave 19, UA-49005 Dnipro, Ukraine, http://orcid.org/0000-0002-1439-1183*

*[2]Dnipro University of Technology, Department of Mining Engineering and Education, Yavornytskoho Ave 19, UA-49005 Dnipro, Ukraine, http://orcid.org/0000-0001-7498-8494*

*[3]Ukrainian State University of Chemical Technology, Department of Technology of Inorganic Substances and Ecology, Haharina ave. 8, UA-49005 Dnipro, Ukraine, http://orcid.org/0000-0002-7747-0911*

*[4]Branch for Physics of Mining Processes of the M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Department of Rock Mass Condition Control, Symphyropilska str. 15, UA-490005, Dnipro, Ukraine, http://orcid.org/0000-0003-3058-4820*

*[5]V. Hnatiuk Ternopil National Pedagogical University, Ternopil, Department of Mechanical Engineering and Transport, Ternopil, M. Kryvonosa str. 2, UA-46000, Ukraine, http://orcid.org/0000-0002-5327-6938*

*[6]AGH University of Science and Technology, Faculty of Management, al. Mickiewicza 30, Krakow, 30059, Poland, http://orcid.org/0000-0002-3143-8940*

**Abstract**

Experimental methods for determining a performance index of explosives are analysed: the methods of a ballistic pendulum, ballistic mortar, a lead block, and according to the volume of soil explosion funnel. It is defined that the determination of a performance index of emulsion explosives (EE) involves a set of significant features connected with a large critical diameter requiring the experiments with large-mass charges and resulting in refusal from the traditional methods of determining a performance index. Analytical methods for calculating an index of relative performance of explosives are analysed. Determination of the performance indices of explosives with the help of analytical methods helps identify considerable differences in the calculation results; in case of emulsion explosives the results are erroneously low at all. It is since analytical methods do not consider the brisant action of emulsion explosives. This paper represents the developed methodology of determining a performance index of explosives according to the degree of detonation velocity. The proposed methodology considers the key energy and detonation characteristics of explosives: heat and volume of the explosion products, density (thickness), and detonation velocity. The use of analytical methodology for calculating a performance index for all explosive types makes it possible to get correct results that are necessary for designing the parameters of drilling and blasting operations.

**Keywords:**

emulsion explosive; drilling and blasting; performance index; energy and detonation characteristics; detonation velocity

## 1. Introduction

Managing the blasting processes during ore extraction is a very important process since the efficiency of all mining processes performed with the help of drilling and blasting depends on it. Increasing the capacity of an explosion does not always have a final positive effect. That is why the economic assessment of high-budget projects, which includes drilling and blasting works, requires a comprehensive analysis performance of explosives and managing of the blasting process (**Dychkovskyi et al., 2013**). Also, it is worth considering the historical aspects of the application and managing the explosives in mining.

Corresponding author: Roman Dychkovskyi
*e-mail address: Dychkovskyi.r.o@nmu.org*

Mining operations began to use explosives at the beginning of the 17$^{th}$ century. It is considered that the development of blasting operations started with the advance of new explosives and initiation devices in the 1850s; in general, that was stipulated by the rapid progress of mining industry worldwide. In the early 20$^{th}$ century, the mining industry got a new explosive – trinitrotoluol (trotyl, tol), having become the most widely used explosive substance. Mining enterprises have been still using trotyl in the form of trotyl-containing explosives. It is known that blasting operations with the use of this explosive result in considerable atmospheric emissions of hazardous substances in the forms of nitrogen oxide and carbon oxide (**Mironova and Borysovs'ka, 2014**); that greatly impact both the environment and human health (**Myronova, 2016**). Thus, trotyl is prohibited to be used for industrial purposes all over the world. Locally produced analogues are the alternatives to substitute trotyl-containing explosives (**Fedko et al., 2014**); they include the explosive materials not containing trotyl and emulsion explosives (**Kholodenko et al., 2014**). The latter are safe during their transportation (**Lyashenko et al., 2022**) and storage (**Krysin et al., 2004**), environmentally safe (**Kholodenko et al., 2015**) and economically expedient (**Kononenko et al., 2022**).

According to the "Central Regional Programme of Mining Enterprise Transferring to the Non-trotyl Environmentally Friendly Explosives", the Programme developed by joint efforts of the mining enterprises of Kryvyi Rih and implemented in 1999, ore and non-metallic open pits started transferring to the use of new non-trotyl explosives beginning from 2004 (**Stupnik et al., 2022**). As far back as in 2011, the use of such explosives in open-pit mining enterprises reached 99%. That has resulted in the fact that in recent years, Ukraine has witnessed certain changes in the methods and technology of blasting operations, a range of explosives and products of their basis has expanded, including the ones obtained because of the disposal of ammunition and solid rocket fuel. In particular, the nomenclature has been expanded along with the increased consumption volume of the explosives made from non-explosive materials immediately within the area of blasting operations. Some mining enterprises have constructed their own facilities to manufacture emulsion explosives with the use of national or foreign technologies and equipment **(Dychkovskyi et al., 2021)**. That has allowed for a considerable increase in the level of environmental safety and improved blasting efficiency under different mining and geological conditions. However, the enterprises dealing with underground mining methods (**Kosenko, 2021a**) use mostly trotyl-containing explosives (**Kosenko, 2021b**). Thus, in 2012 the "Target Regional Programme of Mining Enterprise Transferring to Non-trotyl Environmentally Friendly Explosives" started to be implemented for those mining enterprises as well. In this case, technological features and automation in the drilling and blasting preparation play an important role (**Heyduk and Joostberens, 2022**)

Underground iron ore mining is implemented to the full extent by drilling and blasting operations (DBO) involving industrial explosives (IE), among which 58% are currently emulsion explosives. Depending on the fact how correct the DBO parameters are calculated, technical and economic indices of mine working drivage (**Khomenko et al., 2019**) and ore breaking while stoping (**Khomenko et al., 2018**) can experience certain changes. The detonation velocities of various explosives involve examining their characteristics and performance under controlled conditions. Detonation velocity refers to the speed at which a detonation wave travels through an explosive material. It is an important parameter that determines the power and effectiveness of an explosive (**Polyanska et al., 2022**). It is proven that the angle of blasting drillings has an influence in the cost of mining. It depends on various factors such as the geological conditions, desired fragmentation, safety considerations, and the intended purpose of the blast. In mining, the angle of drilling is determined based on the type of rock or ore being extracted, the shape of the resulting rock fragments, and the location of the blasting site. The angle can vary widely but is typically selected to optimize the efficiency of the blast and ensure the safe extraction of materials (**Brahimaj et al., 2022**). Determining the detonation front curvature radius involves analysing the characteristics of the explosive material and the conditions under which it is detonated. The curvature radius of the detonation front refers to the radius of the curved shock wave produced by the detonation and is a very important parameter for providing successful DBO (**Štimac Tumara et al., 2022**). A performance index of the selected explosive influences the determination of specific explosive consumption while DBO designing. First, that is important while applying emulsion explosives as their performance index depends on numerous factors, especially on the charging density (**Kononenko et al., 2021**). The formation of models for estimating the parameters of explosive works is an important process. Models are not completely studied even though they are seriously represented in specialized literature. For example, the implementation of π-models (**Vladyko et al., 2022**) or the Wood-Kirkwood model (**Štimac Tumara et al., 2022**), which presents a mathematical apparatus used for describing the behavior of polymer solutions, were successfully implemented for mining using DBO.

Different explosives have varying detonation velocities due to variations in their chemical composition, density, and physical properties. The authors provide an analysis of the detonation velocities of various explosives, which are indeed variable in different sources, but are well known. The main object of the study is the installation of this parameter for the emulsion explosive "Ukrainit". As part of this research, a new method for determining the performance of explosives was developed.

The conducted analysis shows that it is necessary to improve the existing methods for determining the performance of explosives and blasting managing. For this purpose, the authors analysed the available techniques and made a generalization of the methods for the explosive usage in the extraction of ore deposits.

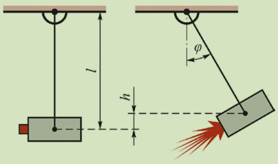
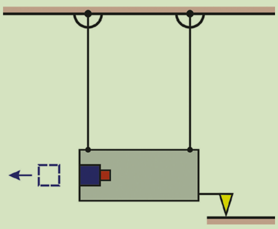
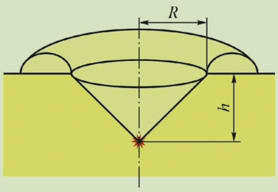
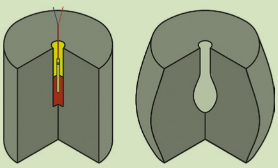
## 2. Research methodology

### *2.1. Implementation the detonation velocity*

Development of the methodology for defining the IE performance index considering a degree of implementing a detonation velocity included the following stages:

1. Analysis of the experimental methods for determining a performance index of the selected explosive;

**Table 1:** Characteristic of the experimental methods for determining a performance index of explosives

| Method | Scheme | Advantages and disadvantages |
|---|---|---|
| Ballistic pendulum |   | The advantage of this method is in the possibility to test large charges being more than 200 g. However, the disadvantage is that the pendulum does not allow the evaluation of absolute and relative performance values due to complex conditions and low or undefined degree of expansion of the explosion products, which can differ from the real ones. |
| Ballistic mortar |  | Ballistic mortar is an accurate instrument. However, it has the following disadvantages: light weight of the explosive mass that prevents from analyzing simple and water-containing explosives and emulsion explosives, the majority of which react only in terms of large charging diameters. The initial state of an explosive corresponds to the improbable low charging density, i.e. the explosive charge should occupy only 2-5 % of the chamber volume. It is especially undesirable in terms of such low charging density the explosive heat often appears to be too low at the insignificant performance index or pressure. |
| Soil explosion funnel |   | The advantage of this method is as follows: it helps test the charges of considerable weight in terms of practical application. The disadvantages include poor reproducibility and low accuracy. |
| Lead block (Trauzl test) |  | Its advantage is its simplicity. The disadvantages include the following: performance indices of the explosives are expressed in certain conventional units of the volume increment. Besides, it is impossible to compare explosives quantitatively according to the value of hole expansion; one can range them only in some relative mode. A disadvantage is also the large mass of the block reaching about 70 kg as well as the high cost of the test since the block should be remolten and recast before each test. |

2. Study of the methods to calculate a performance index of the explosive;
3. Development of the methodology to calculate a coefficient of relative performance index of all IEs concerning the degree of implementing a detonation velocity.

Analytical methodology for determining a coefficient of relative performance index of all IEs is based on the comparison of maximum possible detonation velocity of some explosive and its real values obtained under the field conditions.

Analysis of the most known methods for calculating the IE parameters during the mine working drivage (**Kononenko et al., 2019**) and ore breaking (**Khomenko et al., 2018**) has helped identify that the proposed computational formulas for determining a line of least resistance (LLR) of blasthole and borehole charges use a coefficient of relative performance index of an explosive ($e$) (**Kukib et al., 2017**). This coefficient influences the determination of specific consumption and total mass of the explosive that is necessary for breaking a certain volume of the rock mass. As is known, the term “performance index of IE” means capability of explosives to perform a mechanical operation while blasting owing to the expansion of gaseous explosion products. It should be also noted that any IE is characterized by specific parameters being invariant as for different blasting conditions. To process input and output data, it is quite effective to use various methods of statistical processing and establish priority factors for blasting operations (**Sala and Bieda, 2019**). The parameters are as follows: detonation velocity, charging density, explosion heat, mass expansion velocity of the explosive products, pressure, and specific energy at the Chapman-Jouget point. A theoretical calculation of those values according to the known structural and chemical composition of the explosive is impossible except for explosion heat. This is due to insufficient studies of the processes occurring quickly in a condensed environment at the molecular level. Thus, one can obtain the explosive characteristics required for solving the problems concerning IE parameter calculations only by means of experimental methods of determining a performance index of some explosive (**Kuk, 1980**) and the criteria of its estimations (**Kukib et al., 2017**). Based on this, analyses of the generally known methods are performed for determining the performance index of an explosive and methods in order to calculate its relative performance index.

### 2.2. Experimental evaluation of the performance index of explosives

Currently, the following methods are used for experimental evaluation of a performance index of explosives: methods of the ballistic pendulum, ballistic mortar, a lead block (Trauzl test), and determining the volume of soil explosion funnel (**Kuk, 1980**). **Table 1** represents a brief characteristic of the experimental methods for defining a performance index of explosives.

### 2.3. An analysis of experimental methods for determining the operation of blasting.

For experimental analysis for determining the operation of blasting, the ballistic pendulum method, ballistic mortar method, soil ejection funnel test, and the Trautzl test in a lead block are mainly used (see **Table 1).** The basis of the ballistic pendulum method is a load, suspended on rigid rods to a stationary support. When the pendulum is affected by the products of an explosion or a shock wave, it receives a certain impulse of force and deviates to the appropriate angle $\varphi$. When the explosive is detonated, the center of gravity, placed on the end of the pendulum is rising to a height $h$. Thus, the work of the explosion $A_v$ is spent according to the rise of the center of gravity of the pendulum and can be calculated according to the formula:

$$A_v = m \cdot g \cdot l \cdot (1 - \cos\varphi) \quad (1)$$

Where:

$A_v$ – work of the explosion, J;

$m$ – mass of the pendulum, kg;

$l$ – length of pendulum suspension, m;

$h$ – the height of the center of gravity of the pendulum, m;

$g$ – acceleration of the gravity, 9,81 m/s$^2$;

$\varphi$ – deviation angle of the pendulum, degree.

According to the ballistic mortar method, an explosive charge and a projectile are placed in the opening of a freely elevated mortar-pendulum. When an explosive device explodes, the projectile is ejected from the mortar, which is deflected due to recoil at a certain angle. The total work $A_v$, spent on the deflection of the mortar by the angle $\varphi$ is calculated according to the formula:

$$A_v = M \cdot g \cdot l \cdot (1 - \cos\varphi)\left(1 + \frac{M}{m}\right) \quad (2)$$

Where:

$A_v$ – work of the explosion, J;

$M$ – mass of the mortar, kg;

$h$ – elevation height of the mortar center of the gravity, m;

$l$ – mortar suspension length, m;

$m$ – piston mass, kg.

The funnel test of soil release is based in level of the soil deformation. When a concentrated explosive charge located in sandy soil at a depth fixed for this series of studies explodes, a cone-shaped funnel with a certain radius and depth is formed. As the results of numerous experiments have shown, the volume of the formed funnel is proportional to the efficiency of the explosive charge and can be determined by the formula:

$$A_v \sim V = \frac{1}{3} \cdot R^2 \cdot h \quad (3)$$

Where:

$A_v$ – work of the explosion, m$^3$;

$R$ – funnel radius, m;

$h$ – depth of the funnel, m.

The most simple and widespread method of practical evaluation of the relative efficiency of explosives is the test according to the Trautzl method in a lead block. The block in created in the form of a cylinder. It is made from refined lead and has the following parameters: a height of 200 mm and a diameter of 200 mm. When determining explosive performance by the Trautzl method, the change in initial and final volume is considered, so temperature is not considered in this method. An explosive charge weighing 10 g with an electric detonator is placed in a block hole with a diameter of 25 mm and a depth of 125 mm. The hole is filled with sand. After the explosion, a pyriform cavity with a volume of $V_k$, is created. The volume of this cavity, after deducting the initial volume of the opening $V_p$ (61-65 cm$^3$) and the volume of expansion, which is performed by the electro detonator (approximately 30 cm$^3$), is a measure of relative efficiency of this explosive and is determined by the formula (**Locking, 2022**):

$$A_v = V_k - V_p - 30 \quad (4)$$

Where:

$A_v$ – work of the explosion, cm$^3$;

$V_k$ – the value of the final volume of the pyriform cavity after the explosion, cm$^3$;

$V_p$ – the value of the initial volume of the hole before the explosion, cm$^3$.

An analysis of the advantages and disadvantages of determining the explosives performance, using the above methods is given in **Table. 1**.

Analysis of determining the performance indices of explosives with the help of experimental methods has proven that the studies of explosive properties of EE have certain considerable advantages connected with their critical diameter. On the one hand, a large critical diameter makes it possible to greatly mechanize their production and immediately use products within the area of blasting operations (**Dychkovskyi, 2015**). On the other hand, that requires carrying out the experiments with large-mass charges that will result in refusal from the traditional forms of determining the performance indi-

**Table 2:** Methods to calculate a performance index of explosives

| Method type | Author | Formula | Factor | | | |
|---|---|---|---|---|---|---|
| | | | Explosion heat, kJ/kg | Volume of the explosive products, l/kg | Density (thickness) of the explosive, kg/m$^3$ | Detonation velocity of the explosive, m/s |
| By explosion heat | Proposed according to the lead block tests (Trauzl test) (**Ugolnikov and Simonov, 2007**) | $e = \frac{Q_E}{Q_{VR}}$ | + | – | – | – |
| By action of the explosive products | Andrieiev, K.K., Bieliaiev, O.F. (**Ugolnikov and Simonov, 2007**) | $e = \frac{A_E}{A_{VR}}$ | + | + | – | – |
| | Kuznietsov, V.M. (**Kuznetsov and Shatsukevich, 1978**) | | | | | |
| By relative explosive capacity of the explosive | Johansson, C., Langefors, U. (**Johansson and Langefors, 1972**) | $e = \frac{1}{s}$ | + | + | – | – |
| | Kuznietsov, V.M. (**Kuznetsov and Shatsukevich, 1983**) | | | | | |
| By the Trauzl test | Afanasenkov, A.M. (**Afanasenkov, 2004**) | $e = \frac{1}{f'}$ | + | + | – | – |
| By the explosive yield | Pupkov, V.V., Maslov, I.Yu., Syvenkov, V.I. et al. (**Pupkov, 2005**) | $e = \frac{E_{VR}}{E_E}$ | + | – | + | + |

ces with the help of the Trauzl test in a lead block and testing in a ballistic mortar or pendulum. Thus, relative performance indices for EE should be defined involving analytical methods of calculation. **Table 2** analyses the known methods for calculating a relative performance index of explosives.

The formulas for calculating the performance index of explosives represented in **Table 2** considers only the energy of an explosion and gas emission of an explosive yield; then the volume of explosive gases is not considered. However, rock breaking cannot be determined only by the expansion action of the explosion products. As is known, a part of energy is consumed for the formation of a blast wave transferring into a stress wave along with the distancing from the charge (**Kononenko and Khomenko, 2021**). Accordingly, the expansion of the methodology for establishing the performance of explosives to these parameters is an important scientific and practical task that requires an urgent solution. It also allows for the expansion of the limits of application of the mentioned methods and makes it possible to further establish the economic indicators of drilling and blasting of all mining processes.

## 3. Results and discussion

As a result of the proposed approaches to the assessment of the blasting performance and research methodology, a method of establishing the workability of explosives and its effectiveness in various mining and geological conditions was developed. Internationally known explosives and explosives, which were developed by Ukrainian scientists, were taken into consideration. The proposed methods make it possible, if necessary, to establish the performance of other explosive substances. The correctness of the approaches was verified by the practical implementation of the results in the mining and geological conditions of Ukrainian mines.

While exploding, a compression zone is formed with the blast wave radius, i.e. a shear zone where rock is broken into fractions less than 1 mm. Here, there is an action of a brisant component of explosion determined by the detonation velocity and density of the explosive. Consequently, it is necessary to develop a methodology for calculating a performance index to consider not only the energy of explosion and gas emissions but also the brisant action of the explosives, i.e. detonation characteristics of all IEs.

As an example, calculations for the performance indices of all industrial explosives used during the iron ore mining at the mines of Ukraine were performed. The results of the calculations of performance indices of the explosives according to the available methods are shown in **Table 3**.

Based on the data presented in **Table 3**, a histogram was created for clarity of the reproduction of the value of

**Table 3:** Performance indices of the explosives according to different methods

| **Parameters** | **Ammonite No.6 ZhV** | **Grammonite 79/21** | **Ukrainit-P-SA** | **Ukrainit-PP-2** | **Ukrainit-ANFO (KM-1)** | **ANFO** |
|---|---|---|---|---|---|---|
| Initial data for calculations | | | | | | |
| Density (thickness), kg/m$^3$ | 1100 | 1000 | 1150 | 1250 | 850 | 850 |
| Explosion heat, kJ/kg | 4316 | 4291 | 3900 | 3100 | 3800 | 3800 |
| Volume of explosion products, l/kg | 895 | 895 | 825 | 840 | 985 | 966 |
| Detonation velocity, m/s | 4100 | 3600 | 5050 | 5100 | 3600 | 3500 |
| Calculated performance index *e* according to: | | | | | | |
| explosion heat | 1.00 | 1.00 | 1.11 | 1.39 | 1.14 | 1.14 |
| action of explosion products | 1.00 | 1.00 | 1.09 | 1.19 | 0.99 | 1.01 |
| relative explosive capacity | 1.00 | 1.00 | 1.09 | 1.19 | 0.99 | 1.01 |
| Trauzl test (Afanasenkov, A.M.) | 1.00 | 1.00 | 1.10 | 1.30 | 1.07 | 1.08 |
| explosive yield | 1.00 | 0.79 | 1.16 | 1.02 | 0.60 | 0.58 |

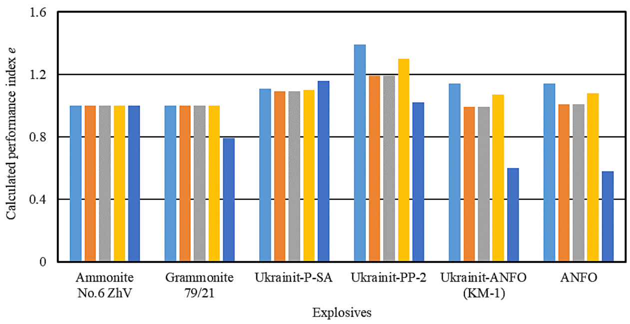



**Figure. 1:** Histogram of the value of the performance explosives coefficient, calculated using different methods: – explosion heat; – action of explosion products; – relative explosive capacity; – Trauzl test (Afanasenkov, A.M.); – explosive yield

the explosive's efficiency coefficient, calculated by various methods is presented in **Figure 1.**

Analysis of the results of calculating the performance indices of different explosives in terms of the available methods represented in **Table 3** has made it possible to make following conclusions:

– a relative performance index of the explosives calculated according to explosive heat has a greater value compared to the results of calculations involving other methods; it indicates that other methods consider the additional action of other factors such as volume of the explosion products;

– the values of performance indices of explosives calculated in terms of action of the explosion products and a relative performance index are of similar magnitude owing to insufficient consideration of explosion energy and excessive consideration of gas emission.

– if we compare the results of calculating a performance index of explosives by the Trauzl test (Afanasenkov, A.M.) with the previous two methods, the obtained values will be a little bit higher demonstrating the excessive consideration of explosion heat and insufficient consideration of gas emissions;

– a performance index calculated according to the explosive capacity has lower values as this method considers brisant characteristics of explosives and explosion heat but does not consider the volume of explosion gases.

The use of different explosive types with different detonation characteristics while driving mine workings and breaking rock masses stipulates the necessity to determine a performance index of a reference explosive, i.e. Ammonite No.6 ZhV, which is used as an industrial reference explosive in Ukraine. (**Falshtynskyi et al., 2020**). However, the known methodologies define a performance index in terms of a combination of different explosive indices that results in differences in the obtained calculation results; in case of EE the results are erroneously low at all. Owing to that, a performance index for IE is proposed to determine considering a degree of implementation of detonation velocity that will help consider energy and detonation characteristics of explosives such as heat and volume of the explosion gases as well as density and velocity of the explosive detonation (**Kulynych et al., 2021; Serdaliyev and Iskakov, 2022**). It is offered to calculate IE performance index according to new methodology as follows:

– ideal detonation velocity;

– degree of implementation of the detonation velocity;

– explosion heat as for a degree of implementation of the detonation velocity;

– performance index in terms of implementation of the detonation velocity, i.e. according to the chemical reaction completion.

The ideal detonation velocity, i.e. maximum possible at the specified density (thickness) of an explosive, is determined according to the formula proposed by Chinese researchers (**Kononenko et al., 2019**):

$$D_i = 2641 + 3.231 \cdot \rho \cdot \sqrt{Q_{VR} \cdot V_{PV}} \qquad (5)$$

where:

$D_i$ is the ideal detonation velocity, m/s;

$\rho$ is density (thickness) of an explosive, g/cm$^3$;

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**Table 4:** Results of the calculations of energy and detonation characteristics of different composite and emulsion explosives

| Parameter | Ammonite No.6 ZhV | Grammonite 79/21 | Ukrainit -P-SA | Ukrainit -PP-2 | Ukrainit-ANFO (KM-1) | ANFO |
|---|---|---|---|---|---|---|
| Density (thickness), g/cm$^3$ | 1.10 | 1.00 | 1.15 | 1.25 | 0.85 | 0.85 |
| Explosion heat, kcal/kg | 1030 | 1024 | 931 | 740 | 907 | 907 |
| Explosion heat, kJ/kg | 4316 | 4291 | 3900 | 3100 | 3800 | 3800 |
| Volume of explosion products, l/kg | 895 | 895 | 825 | 840 | 985 | 966 |
| Experimental velocity of detonation, m/s | 4100 | 3600 | 5050 | 5100 | 3600 | 3500 |
| Ideal velocity of detonation, m/s | 6053 | 5270 | 5897 | 5825 | 5237 | 5212 |
| Degree of detonation velocity implementation, % | 68 | 68 | 86 | 88 | 69 | 67 |
| Explosion heat considering a degree of detonation velocity implementation, kJ/kg | 2923 | 2931 | 3340 | 2714 | 2612 | 2552 |
| Performance index of an explosive | 1.00 | 1.09 | 0.88 | 1.08 | 1.12 | 1.15 |

$Q_{VR}$ is explosive heat of an explosive, kcal/kg, determined by dividing value $Q_{VR}$ in kJ/kg by coefficient 4.19 (mechanical equivalent of heat energy);

$V_{PV}$ is volume of the explosive products, l/kg.

A degree of the implementation of a detonation velocity, i.e. the completeness of a chemical reaction, is defined according to the expression

$$\eta_x = \frac{D_e}{D_i} \cdot 100 \qquad (6)$$

where:

$\eta_x$ is the degree of the implementation of a detonation velocity, %;

$D_e$ is experimental detonation velocity, m/s.

Explosion heat considering a degree of detonation velocity implementation is

$$Q = \frac{Q_{VR} \cdot \eta_x}{100} \qquad (7)$$

where:

$Q$ is explosion heat considering a degree of detonation velocity implementation, kJ/kg;

$Q_{VR}$ is explosion heat of 1 kg of an explosive, kJ/kg.

A performance index of the explosive is calculated according to the ratio

$$e = \frac{Q_E}{Q_{VR}} \qquad (8)$$

where:

$Q_E$ is the explosion heat of 1 kg of the reference explosive (Ammonite No.6 ZhV) taking into account a degree of detonation velocity implementation, kJ/kg;

$Q_{VR}$ is explosion heat of 1 kg of the taken explosive considering a degree of detonation velocity implementation, kJ/kg.

As an example, consider the use of the proposed methodology to evaluate a degree of implementation of the potential energy in terms of detonation velocity, i.e. according to the chemical reaction completeness during the explosion of composite explosives and emulsion explosives applied while iron ore mining at the mines of Ukraine. The results of calculations in terms of new methodology of energy and detonation characteristics of different composite and emulsion explosives are given in **Table 4**.

The obtained data of the calculation of energy and detonation characteristics of composite and emulsion explosives (see **Table 4**) have made it possible to conclude that a degree of completeness of chemical reactions of packaged explosive Ukrainit-P-SA and liquid emulsion explosive Ukrainit-PP-2 considerably exceed the composite explosives making up about 86-88%, while in case of composite explosives, this index is within the range of 67-69%. According to this, the actual explosive heat experiences its changes by the same values. Packaged and liquid emulsion explosives of the Ukrainit type demonstrate the highest explosion heat approaching to the calculated one. In this case, packaged and liquid emulsion explosives Ukrainit-P-SA and Ukrainit-PP-2 have a similar much higher detonation pressure that allows for a significant increase in the rock breaking intensity. As the proposed methodology for calculating energy and detonation characteristics of the explosives demonstrates and numerous experimental (**Kozyrev et al., 2020**) and calculation data (**Kononenko et al., 2021**) show, the maximum detonation velocity and relative performance index of the taken explosive is reached at a certain charging density (thickness). As for a value of performance index of the explosives calculated according to the proposed methodology, its magnitude considers the main explosive characteristics: heat and volume of the explosion products, density, and detonation velocity. Considering a performance index of explosives while calculating and designing the IE parameters helps achieve more accurate results (**Fedko et al., 2019; Ishchenko, 2022**).

## 4. Conclusion

Blasting performance management is an important element in mining. Moreover, the excessive capacity of the explosion leads to the destruction of the rock mass. This leads to the deterioration of the situation with the mining pressure management and the emergence of problems with the fastening. The proposed method is an effective mechanism for establishing rational parameters for the use of explosives in mining, which aims to improve mining processes and obtain a positive economic result in mineral extraction.

Analysis of the available method for determining the explosion action and methodologies for determining performance indices of the explosives has helped identify considerable differences in the calculation results; in case of emulsion explosives, the results were even erroneously low as they did not consider their brisant action. Thus, new methodology for calculating performance indices of different IEs in terms of their degree of detonation velocity has been developed.

Energy and detonation characteristics calculated according to this methodology for composite and emulsion explosives have demonstrated that a degree of chemical reaction completeness of emulsion explosives reaches 86-88 % while for composite explosives this index varies within the range of 67-69%. The developed methodology of determining a performance index of the explosives considers basic energy and detonation characteristics of the explosives: heat and volume of the explosion products, density (thickness) and detonation velocity that makes it possible to obtain correct results to calculate and design the IE parameters both while driving mine workings and while breaking an ore mass.

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## SAŽETAK

### Utvrđivanje učinkovitosti eksploziva kod izvođenja miniranja

U radu su analizirane eksperimentalne metode kojima se određuje indeks učinkovitosti eksploziva: metoda balističkoga klatna, metoda balističkoga mužara, Trauzlova proba i metoda određivanja volumena kratera od miniranja u tlu. Utvrđeno je kako određivanje indeksa učinkovitosti emulzijskih eksploziva (EE) uključuje skupinu važnih značajki povezanih s velikim kritičnim promjerom, a to zahtijeva ispitivanja s nabojima velike mase i odustajanje od tradicionalnih metoda određivanja indeksa učinkovitosti. Također, analizirane su analitičke metode za izračunavanje indeksa relativnoga učinka eksploziva. Određivanje indeksa učinkovitosti eksploziva uz pomoć analitičkih metoda pomaže identificirati znatne razlike u rezultatima, a rezultati su u slučaju emulzijskih eksploziva općenito preniski. Do toga dolazi zato što analitičke metode ne uzimaju u obzir brizantno djelovanje emulzijskih eksploziva. U radu je prikazana razvijena metodologija određivanja indeksa učinkovitosti eksploziva prema stupnju brzine detonacije. Predložena metodologija razmatra ključne parametre energije i detonacijskih svojstava eksploziva: toplinu i volumen produkata eksplozije, gustoću (promjer) i brzinu detonacije. Korištenje analitičke metodologije izračuna indeksa učinkovitosti kod svih vrsta eksploziva omogućuje dobivanje točnih rezultata potrebnih za određivanje parametara bušenja i miniranja.



**Ključne riječi:**
emulzijski eksploziv, bušenje i miniranje, indeks učinkovitosti, energija i detonacijska svojstva, brzina detonacije


## Author’s contribution

**Maksym Kononenko** (Dr. Sci. Associated Professor) – description of the problem and analysis of the drawbacks of blasting technologies; development of approaches to the development of the research methodology, performance the preliminary calculation; analysis of research results. **Oleh Khomenko** (Dr. Sci., Professor) – developing the algorithm for calculation and determination of technological parameters; description of the technologies research. **Ihor Kovalenko** (Dr. Sci. Professor) – participation in the formation of a management system of the extraction of mineral reserves, the justification the ecological aspects and rock mass control. **Andrii Kosenko** (PhD., Associated Professor) – forming the mathematical model, conducting the preliminary calculation. **Roman Zahorodnii** (PhD., Associated Professor) **–** processing the results of research, development of graphic elements of the work. **Dychkovskyi Roman** (Dr. Sci. Professor) – forming the object and the subject of the research; development of the idea of work and the methodology for achieving results; analysis of research; description of the data for the development of mining processes.