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Selection of the optimal composition and analysis of the detonating characteristics of low-density mixed explosives applied to break thin ore bodies

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Abstract

Purpose is to select the optimal composition of the mixed low-density explosive (*Es*) applied in the form of blasthole charges which provide high efficiency of blasting operations while mining of thin ore deposits. The abovementioned becomes possible while studying features of the foamed polystyrene chemical decomposition and gasification; role of additional water components as well as catalyzator being sodium carboxymethyl cellulose; and analysis of explosive characteristics of the compositions.

Methods. The research involved lab-based experiments to define application efficiency of the recommended low-density blasting agents through identification of the basic explosive characteristics of the model mixed *Es*.

Findings. The optimal composition of the mixed low-density *Es* has been developed. It consists of ammonia nitrate, diesel fuel, granulated foamed polystyrene, water, and sodium carboxymethyl cellulose to be used to break thin ore bodies. Owing to it, the possibility has arisen to control over a wide range both detonation velocity and pressure of blasting fumes during the charge density increasing or decreasing. The main detonative characteristics of the proposed compositions of low-density *Es* have been determined helping perform explosive rock mass loading in terms of extremely low values of both energy and explosive characteristics. The developed composition of the mixed low-density *Es* makes it possible to control quantity of *Es* energy in a volume well unit by means of increase or decrease in the charge energy concentration depending upon the changes in the rock mass resistance; in such a way, efficient breakage of thin ore bodies is provided inclusive of less dilution indicators.

Originality. For the first time, dependence of the relative efficiency of the mixed low-density *Es* upon the foamed polystyrene volume content has been identified as well as dependence of pressure of blasting fumes upon the charging density.

Practical implications are the development of procedures for blasting operations while thin ore body mining. The procedures are based upon formulating of the optimal composition of low-density *Es* differing in its simplicity, safety, and efficiency; and helping reduce prime cost of the extracted mineral at the expense of the decreased degree of the ore dilution. An empiric formula to define specific consumption of the low-density *Es* has been proposed for Akbakay mine.

Keywords: *rock mass, ore deposits, breakage, mining, dilution, ore, explosive, charge density*

1. Introduction

The majority of thin deposits in Kazakhstan are characterized by complex mining and geological as well as morphological structure of ore deposits; nonuniform distribution of minerals; dense fissuring of formation; tectonic disturbances; and variable physicomechanical characteristics of ore minerals and enclosing rocks [1]-[4]. Thinness of the ore deposits, combined with the complicated geological occurrence conditions, results in significant dilution of the minerals during their excavation. Generally, complete mining, and sublevel-chamber system (where ore is delivered with the help of explosive force of deep borehole charges) are applied. Consequently, dilution degree may sometimes achieve 70% and more. The situation is typical for the majority of such deposits all over the world [5]-[7].

Relying upon the earlier research, concerning extraction of thin ore deposits (i.e. 0.9-1.5 m), the authors have identified that breakage of ore bodies from sublevel drifts through deep blasthole charges factors into dilution in blocks at the expense of enclosing rock blasting from a bottom wall and a hanging wall; its value may achieve 75%. For example, in the context of Akbakay mine, rock breaking from a hanging wall is 0.4-0.6 m if ore bodies with an average 1.2 m thickness are mined; the figure is 0.2-0.3 m in terms of a bottom wall. In this vein, quality of thin ore body breakage influences heavily the ore dilution as well as indicators of all following mining and processing operations causing significant damage to the mine and preparation plant [8]-[10].

The problem concerns not only Akbakay mine. Currently, many ore producers, engaged in mining of thin metalliferous deposits, face difficulties with the mineral extraction; particularly, it is typical for complex mining and geological conditions characterized by disturbances of the enclosing rock mass [11]. If thin ore deposits are mined within unstable for-

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mation, indices of sublevel-chamber system with layer-by-layer ore breaking by means of deep wells and delivery through explosive force drop sharply [12], [13]. Excavation of thin ore deposits, taking place under the conditions of the restricted stope width, makes it possible to improve the ore grade owing to decrease in the primary dilution [14]. However, if deep blasthole charges are exploded in the limited space, a significant share of the explosive energy is consumed by earthquake effect towards the rock mass depth as well as by extra defragmentation of the ore being extracted [15], [16]. In case of unfavourable fissuring distribution, earthquake effect of an explosion results in the mined formation loosening with following potential rock separation from the roof [17]. The abovementioned degrades the ore due to the intensified secondary dilution and complicates mining operations [18]-[21].

In such a way, ore extraction in narrow stopes is subject to the difficulties connected with the conflicting requirements as to its results. On the one hand, breakage procedure as well as the defined parameters of drilling-and-blasting operations (DBOs) should provide high efficiency [22]-[26]. Nevertheless, on the other hand it is required to comply with the geometry of mining operations; minimize amount of rocks being separated; and provide uniform defragmentation of the extracted ore with minimum formation of fine and coarse fractions [27], [28]. Meanwhile, simultaneous fulfillment of the requirements turns out to be extremely challenging. If ore is broken from stable formations of enclosing rocks, then the drive towards high productivity is not always followed by the mineral degradation; at the same time, such a compromise is not always achievable in case the ore is extracted from unstable formations. In general, more attention should be paid to the quality improvement at the expense of decline in output.

Under the specific conditions of underground mineral mining and at the certain stope width, selection of rational blast parameters is the important factor to achieve optimal balance between quantitative and qualitative characteristics of a breakage procedure [29]. Obviously, identification of the efficient relation between a stope width and explosion characteristics during mining of thin ore bodies with varying physicomechanical characteristics of ores and enclosing rocks is the essential tendency for further improvement of a mine throughput.

As it has been mentioned, development of extraction procedures for thin ore deposits should take into consideration all factors influencing formation integrity inclusive of blast loading. It is known that if brisant industrial *Es* are applied, significant blast energy falls at such inefficient and sometimes hazardous processes as plastic strain and intensive rock defragmentation in the immediate vicinity of the explosion; formation of seismic waves; etc. Moreover, certain energy share is also lost if charges have been calculated incorrectly and the unused heat escapes into the atmosphere together with explosion products, or is wasted on excessive scattering of the broken rocks [30]. The abovementioned reduces the explosion efficiency influencing negatively on the whole procedure of ore mining [31].

According to specificity of their composition, industrial blast agents have strictly defined the energy content per unit of volume as well as certain explosion yield. However, the latter may be too high for the majority of cases when it is applied for mining of thin ore bodies; hence, the explosion will have negative results [32]. The condition focused scientists and researchers from our University on the design of such compositions of explosives which would help form *Es* charges with the controlled energy at the blast site.

Review and analysis of both national and world practices of underground mineral mining have shown that one of the promising tendencies in the area, providing the required mechanism of rock breakage, is a method of blast energy control. The method should be based upon the development of rational *Es* charges with the regulated charging density [33], [34]. In other words, the idea involves selection of optimal composition of the mixed low-density explosives (LDEs) with the possibility to control their energy characteristics. As it is known, the *Es* are based upon ammonia nitrate and granulated foamed polystyrene. In this context, it is possible to control destructive action of the low-density *Es* with the minimization of energy transfer to an explosive wave through a simultaneous decrease in volume concentration of the blast energy; detonation velocity; gas amount in the unit volume of the *Es*; and pressure in the charging cavity. The abovementioned is achieved while varying bulk density of the charge.

Earlier, many researchers assumed that in the mechanical mixtures of ammonium nitrate *Es* and the granulated foamed polystyrene the latter acted as a combustible charging material as well as density controller [35], [36]. At the same time, some scientists [37] considered the foamed polystyrene as inert charging material and combustible additive, which could react owing to the initial explosive decomposition of such active components as ammonia nitrate, trinitrotoluol, and others. Nevertheless, based upon the analysis of gas products upon detonation, Norwegian scientists [38] have concluded that within the mixture, foamed polystyrene cannot react chemically. The conclusion relies upon the fact that foamed polystyrene addition to the mixture, containing ammonia nitrate and diesel fuel with the balanced oxygen content, did not demonstrate increase in the emission of toxic gases.

Use of the mixed low-density *Es* makes it possible to control the quantity of energy in a well volume unit through certain changes in the charge energy concentration depending upon variations in the rock mass resistivity or in physicomechanical characteristics of rocks and ore. The abovementioned helps save costs of expensive *Es* and improve blast efficiency. A loading effect on the rock mass on the explosion of low-density *Es* charges results from their energy and detonation characteristics as well as from the detonation mechanism features.

Consequently, an analysis of the basic explosive characteristics together with the definition of optimal composition of the mixed low-density *Es*, which can be used as charges for wells and provide high efficiency of blasting operations while thin ore deposit mining, are the topical problem in the context of vein formation extraction under the complicated mining and geological conditions. To solve the problem, specific research has been performed which findings are represented in the paper.

2. Materials and methods

The research involved a complex technique comprising theoretical studies of low-density mixed *Es* operation, and lab-based experiments on the basis of the studies; the proved private procedures were applied in addition to the modern equipment use. The obtained experimental data were processed with the help of mathematical statistics methods to derive dependencies describing the analyzed activities.

The industrial mixed *Es*, incorporating the granulated foamed polystyrene, are heterogenetic explosive systems. The abovementioned is stipulated by the possibility to control broadly the charge characteristics; detonation parameters; detonation wave shape; and, hence, improvement of the efficiency of different types of blasting operations. It should be mentioned that the possibility to control both mode and parameters of an explosion is also connected with the fact that detonation parameters of the mixed *Es* vary significantly depending upon the structure and geometry of grains being in their composition.

2.1. Selecting components of explosive mixtures

Taking into consideration blasting conditions during thin ore deposit mining, selection of explosive mixture components should meet following criteria:

– the selected components have to provide reliable detonation of the mixed low-density charge in blastholes;

– the components should be economically accessible and preferably inexpensive;

– incorporation of new components must not complicate a process of the *Es* formulation;

– the components should be safe, and easy to use and store.

The basic components, used for the mixed low-density *Es*, are granulated ammonia nitrate (GAN), diesel fuel (DF), which pluses and minuses are widely known in the capacity of igdanite and granulated foamed polystyrene (GFP) of PSV class. Use of such a synthetic material as polystyrol of combustible PSV class as the mixed explosive component depends upon the fact that polystyrol microspheres, located among *Es* granules in a certain proportion (i.e. 20-90%), favour control of the mixture density within the range of 0.95-0.25 g/cm³ (Fig. 1). The abovementioned is achieved at the expense of low polystyrol bulk weight being 0.015-0.03 g/cm³) which participates synchronously in the chemical decomposition of the blast agents.

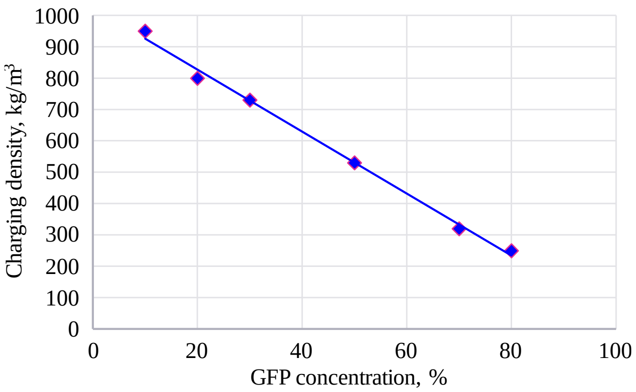

Figure 1. Dependence of the charging density of low-density Es upon the granulated foamed polystyrene ratio

Being a hydrocarbon compound, foamed polystyrene comprises 89.8% of carbon; 8% of hydrogen; 0.18% of sulfur; 0.21% of nitrogen; and 1.8% of oxygen. The material is a styrol polymer which composition includes a sponging agent isopentane which boiling point during polymerization is 27.9ºC [39]. Polystyrol of a combustion PSV class is the specific material differing in high-grade inhomogeneity and microstructure being similar to a foam composition. Its structure is represented by more or less organized layers of polymeric basis, which form walls of gas-filled cells. The physical inhomogeneity as well as alternation of solid and gaseous phases define unique characteristics of the material. Geometric pattern of the cells and their dimensions; free motion of a gaseous phase; and ratio between polymeric and gaseous phases are among the factors characterizing the foamed polystyrene structure and influencing its properties.

The foamed polystyrene ability for complete or partial gasification at high temperatures is among the important characteristics attracting attention in the context of detonation analysis of low-density *Es*. The study has shown that if foamed polystyrene density increases up to 0.02 g/cm³ then its complete gasification in the charge with a similar length is achieved through the direct contact with the initiating charge. Further, increase in density factors into the formation of numerous solid explosion products. In such a way, the basic factors, influencing detonation process of the mixed low-density *Es*, are density and elasticity of the foamed polystyrene granules; pressure within the chemical reaction zone; pressure of expanding explosion products; intensity of energy flow; activation energy of the mixture components; and rate of their decomposition.

In addition to ammonia nitrate, diesel fuel, and granulated foamed polystyrene, water and alkali salts are applied as extra components. To achieve uniform charge structure in blastholes, decrease in dusting, prevention of electrization, and reduced sensitivity to electrical spark discharges, the basic components are added by a structuring agent. It has been identified that sodium carboxymethyl cellulose (Na-CMC) is the most efficient and available structuring agent.

Being a component of the mixed low-density *Es*, water offers significant advantages owing to its multifunctionality. In addition to its role of ammonia nitrate and foamed polystyrene decomposition catalyst as well as steam generator within a zone of chemical reaction of detonation wave, water also acts as a wetting agent preventing a charge separation into layers. Moreover, water is a thermal medium while polystyrol foaming. Water use to wet the foamed polystyrene granules prevents from static electricity accumulation at their surface during powered charging.

Na-CMC is also of considerable versatility. Acting as an ammonia nitrate decomposition catalyzer, a structuring Na-CMC agent is synchronously a catalyzer of hydrocarbon decomposition.

Their operation mechanism is as follows. The matter is that in the presence of salts or owing to the formation of intermediate products, being more active than the initial decomposition products of the *Es* themselves, oxidation of the combustible elements of the molecule is accelerated resulting in formation of such terminal products as CO_2, N_2, and H_2O. Role of Na-CMC, containing alcali metal in the molecule, is to initiate hydrocarbon decomposition with the formation of active products. At the same time, Na transforms rapidly the products at its surface into terminal products. In such a way, one molecule unites catalyzers for decomposition and transformation initiation. Moreover, alkali salts serve simultaneously as catalyzers for carbon oxidation. Use of catalytic transformations at alkali salt surface facilitates reduce in formation of toxic blasting fumes which is extremely important on detonation of low-density *Es* with negative oxygen balance since they have tendency to release substantial quantity of CO as well as hydrocarbon residues. Transformation of the components into H_2O and CO_2 is of double importance. On the one hand, it favours control of toxic gases; on the other hand, it improves thermal efficiency of an explosion while controlling reactions towards maximal energy benefit.

Hence, real opportunities are created for underground use of the mixed low-density *Es*. Moreover, it has been defined that Na-CMC may also be a thermal medium while polystyrol foaming.

2.2. Formulation of the pilot research

Relying upon the above, six samples of the mixed low-density *Es* were produced in a laboratory environment (Table 1). They are recommended to mine thin ore deposits; explosive characteristics of the samples have been analyzed.

Table 1. Compositions of the laboratory samples of the mixed low-density E

Mixture type	Mixture percentage depending upon volume				
	GAN	GFP	DF (over 100%)	Na-CMC (over 100%)	Water (over 100%)
LDE-1	80	20	6.0	0.8	4.0
LDE-2	70	30	6.0	0.8	3.5
LDE-3	50	50	5.0	1.0	3.5
LDE-4	30	70	5.0	1.0	3.0
LDE-5	20	80	4.3	1.1	3.0
LDE-6	10	90	3.6	1.2	3.0

All the applied components are economically accessible; they need not any specific conditions for their storage and transportation. None of the components, included in the proposed composition of a low-density *Es*, is a dangerous material from the viewpoint of safety measures while dealing with them. The basic explosive characteristics of the prepared samples of the mixed low-density *Es* were analyzed in the laboratory using the specific test facility VK-10 for blast assessment studies (Fig. 2).

Figure 2. Test facility VK-10 to analyze physicochemical characteristics of the mixed low-density Es

The mixed low-density *Es* are characterized by low volume density; negative oxygen balance; and inclusion of inert additives. As a rule, the factors result in shifts of chemical behaviour towards the reactions followed by transition of the mixture components to plasma with subsequent compression of the formed plasma with its further blast. In turn, the abovementioned complicates analysis of detonation characteristics of the blast. Hence, some parameters of low-density mixed *Es* samples were defined analytically.

Amount of gaseous products and their composition were identified with the help of 200-gram charge explosion in the specific vessel of the test facility (Fig. 3). 20 grams of finely divided and screened through a sieve #15 trinitrotoluol was applied as an intermediate charge.

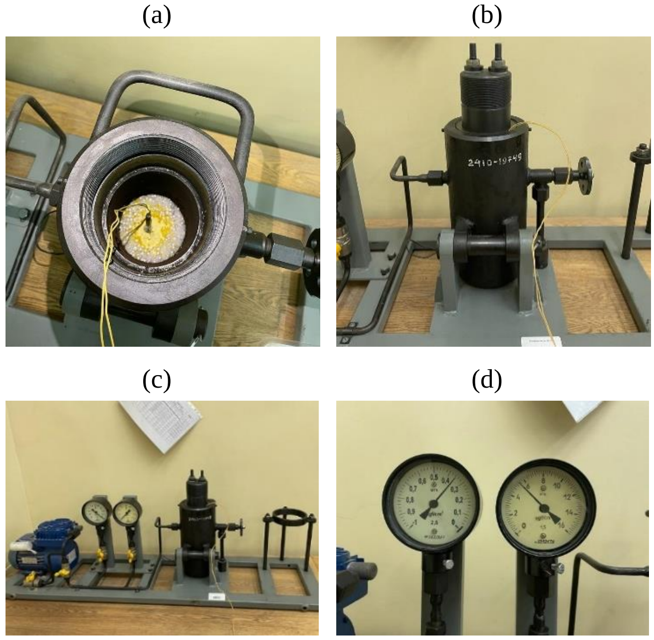

Figure 3. Laboratory tests of the basic detonation characteristics of the mixed low-density Es: (a) tested mixed low-density Es charge; (b) charging chamber of the test facility; (c) initiation of the mixed low-density Es; (d) explosion sensor reading

Instantaneous electric detonators initiated the charge. Failure occurred when LDE-6 sample was initiated; consequently, the composition did not experience any other tests.

Gas was sampled after cooling, i.e. an hour later than the *Es* explosion. Taking into consideration specific composition nature of the mixed *Es* (their low density), the efficiency was defined in terms of lead blocks using an equal charge method relative to 6 ZhV ammonite.

Shattering effect was determined as follows. 50-gram charge of the mixed composition of low-density *Es* was placed in a steel ring with a height of 60-270 mm depending upon the tested sample composition where internal diameter was 40 mm. The steel rings had clean end cuts. Lower end of the ring was sealed by polyethylene to shape a bottom. While charging, the steel rings were filled with the compositions in small portions; slight compaction took place. 10 g of finely divided trinitrotoluol was applied as an intermediate charge.

Detonation mechanism features of the low-density *Es* disagree with the models of hydrodynamic detonation theory; moreover, the geometry of inhomogeneity of a detonation wave front prevents from deriving of the overall dependence through simple generalization of their characteristics in space and time. The detonation completeness was identified in 150-mm cartridges. Cases for them were made of cardboard with 2-mm width.

3. Results and discussion

The laboratory tests have helped identify a composition of explosion products of the mixed low-density *Es*. Table 2 demonstrates the results inclusive of the detailed information on the composition of gases released after blast of the mixed low-density *Es* which is the key aspect while analyzing and optimizing their use to break ore deposits.

Table 3 shows results of the laboratory tests carried out to define the basic explosive characteristics of the mixed low-density *Es*.

Table 2. Composition of explosion products of the mixed low-density Es

Mixture type	Gas volume, l/kg	Composition of explosion products, l/kg									
		H_2	O_2	CO_2	CO	NO_2	CH_4	C_2H_4	C_2H_6	C_3H_6	C_3H_8
LDE-1	628	17.00	0.63	108.0	32.6	5.280	0.088	0.015	0.018	0.0126	0.0012
LDE-2	418	54.00	7.10	80.5	40.2	–	12.950	0.368	0.700	0.084	0.026
LDE-3	230	1.84	–	37.8	14.0	0.050	0.172	0.0207	–	0.0007	–
LDE-4	209	3.13	0.313	21.4	17.6	0.313	0.418	0.056	0.004	0.042	–
LDE-5	199	25.60	4.40	37.6	18.4	0.012	5.6000	0.172	0.320	0.036	0.012

Table 3. Basic explosive characteristics of the mixed low-density Es

Mixture type	Bulk density, g/cm³	Relative efficiency as for 6 ZhV ammonite	Shattering effect, mm	Explosion heat, kkal/kg	Oxygen balance, %	Detonation completeness in cartridges with 150-mm diameter
LDE-1	0.74	0.92	19.05	424.0	+17.4	absolute
LDE-2	0.70	0.98	23.20	466.0	+15.7	absolute
LDE-3	0.53	1.18	21.70	635.0	+10.2	absolute
LDE-4	0.33	1.30	21.40	890.0	–2.0	absolute
LDE-5	0.28	0.89	21.20	743.0	–16.0	failure

As the findings have demonstrated, relative efficiency values for the mixed low-density *Es* have been identified per active charge mass including water and Na-CMC addition. Figure 4 shows dependence of relative efficiency of the ammonia nitrate- foamed polystyrene mixtures upon the volume foamed polystyrene concentration in a charge.

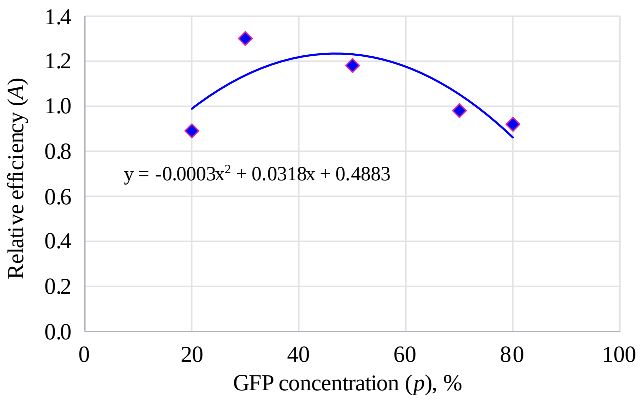

Figure 4. Dependence of relative efficiency of the mixed low-density Es upon the volume foamed polystyrene concentration

Analysis of the graph data has explained that the efficiency of the mixed low-density *Es*, expressed as a ratio between action and mass of active components, achieves its maximum if the foamed polystyrene concentration is about 50%, and remains invariable when the concentration increases up to 80%. Appearingly, high efficiency of the *Es* maintenance depends upon more complete energy release stipulated by the availability of water and catalyzers in the mixture composition. Nevertheless, while accounting inert additions and calculating per charge mass, increase in the foamed polystyrene concentration up to 80% is followed by 20% decrease in the relative efficiency. The abovementioned is connected with the increase in the share of inert additions in the total charge mass.

Determination of pressure of gases, resulting from a blast, is a complex problem since the blast takes place in the compressed plasma volume rather than in the initial volume of *Es*. It should be mentioned that substance volume and density within explosion zone differ greatly from initial parameters. To identify accurately pressure of gases, resulting from detonation, one should have precise data on plasma volume and density at the explosion moment. Average pressure of blasting fumes inside the charging cavity corresponds to the moment of their even distribution within the cavity. Figure 5 shows dependence of the pressure of blasting fumes upon the charge density.

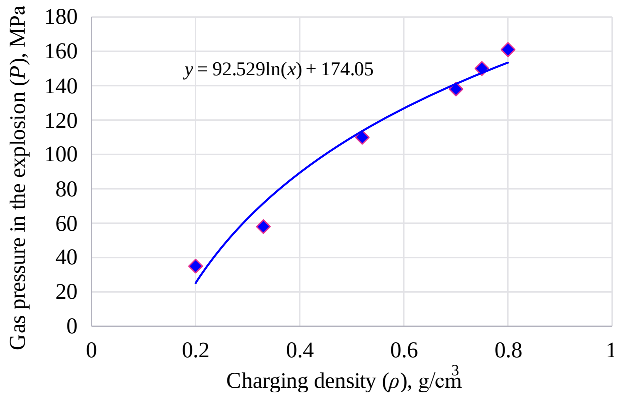

Figure 5. Dependence of the pressure of blasting fumes upon the charge density

At a very high pressure, formed inside a charge chamber during detonation, the density of blasting fumes becomes comparable with the fluid density. In this vein, gas pressure calculation of gases, formed during explosion, should involve volume of molecules of the gases since their influence cannot be ignored. Analytically, blasting gas pressure is identified using the Formula (1):

$$P = \frac{4QE(\Upsilon - 1)}{\pi d^2 L}, \text{ Pa}, \quad (1)$$

where:

Q – the *Es* mass, kg;
E – specific explosion heat, kkal/kg;
Υ – isentropic exponent;
d – charging cavity diameter, m;
L – charge length, m.

While thin ore body mining through blasting, charges in stopes are arranged in lines depending upon the capacity. Traditionally, no less than two lines are used. In some cases, deposit thickness does not correspond to a whole number of lines resulting in the increase of the specific *Es* consumption during defragmentation. The specific *Es* consumption depends upon a degree of free surface width correspondence to the charge diameter as well as a degree of the charge displacement from symmetry axis of the surface.

In such a way, the specific consumption of the mixed low-density *Es* to break ore at tight spaces, and effect of explosion with high volume pressure have to be defined relying upon the total energy equation describing a rock breakage process while blasting (in terms of Akbakay mine):

$$q = 0.19\rho_n \frac{1}{k_g^{0.07}}\left(0.6 + 3.3 \cdot 10^{-3} d_c d_o\right) \cdot \left(\frac{0.5}{S_k}\right)^{\frac{2}{5}} K \text{, t/m}^3, \quad (2)$$

where:

ρ_n – volume rock density, t/m^3;

k_g – defragmentation factor;

d_c – charge diameter, m;

d_o – average jointing size in rock mass, m;

S_k – standard fragment size, m;

K – coefficient, taking into consideration explosion heat of both reference and the applied *Es*, defined using the Expression:

$$K = \frac{Q_r}{Q_e}, \quad (3)$$

where:

Q_r – reference *Es* heat, kkal/kg;

Q_e – applied *Es* heat, kkal/kg.

Industrially, the mixed low-density *Es* are produced using mixing machine. It is recommended to mine water-bearing formation using the mixed low-density *Es* in the packaged form or applying plastic sleeves.

As scientific papers by other researchers [40], [41] mention, the ability of the mixed low-density *Es* to stable detonation at the reduced density is provided owing to the use of foamed polystyrene with 0.005-0.008 g/cm^3 density which amount is 10-90% of the total mass, and addition of catalyzers in the form of water (13-30%) and sodium salt NaCl (6.5-20%).

The results of laboratory tests, carried out by the authors, have made it possible to identify that the use of foamed polystyrene with extremely low density (i.e. 0.005-0.008 g/cm^3) factors into increase in the composition permeability preventing from the uniform sodium chloride distribution along the whole charge length. In addition, it has been defined that decomposition quality during chemical reaction depends upon the charge diameter. In this context, critical diameter should not be less than 150 mm, which restricts underground use of the *Es* composition.

Use of the foamed PSV polystyrene with 0.015-0.03 g/cm^3 density as a component of the mixed low-density *Es* supports uniform catalyzer distribution over the granule surface. Moreover, addition of such a structuring agent as Na-CMC instead of NaCl helps preserve characteristics of *Es* composition in a blasthole over the extended intervals owing to its viscosity and ability to bind the components thus providing conditions for qualitative and rapid ammonia nitrate decomposition during blasting.

It has been identified that if the mixed low-density *Es* are applied then rock mass is loaded in a quasi-static mode with extremely low explosion heat values being 400-1000 kkal/kg. The fact complicates substantiation of the rational application area for the mixed low-density *Es*. Consequently, determination of the regularities, according to which charges of the mixed low-density *Es* operate within a blasting agent-rock contact depending upon both medium resistivity and explosive detonation, needs further research intended to search for optimal ratio between explosive components; effective blasthole diameter involving physicomechanical rock mass characteristics; design of charges; and firing delay intervals. The above-mentioned should expand application area of the mixed low-density *Es*; improve blasting efficiency while thin ore deposit mining; and better their technical and economic performance.

4. Conclusions

The research has helped conclude the following. Correlation between the composition of the mixed low-density *Es* and their characteristics, connected with energy and detonation, has been identified and substantiated scientifically. It has been determined that the ability of the mixed low-density *Es* to stable detonation in terms of extremely low density values (i.e. those ones being less than 0.2 g/cm^3) is achieved owing to the fact that their composition is added by the foamed polystyrene, which density is 0.015-0.03 g/cm^3, as well as by water and structuring Na-CMC agent distributed uniformly over the foamed polystyrene granule surface. Water and sodium carboxymethyl cellulose evaporate at the expense of energy released in the foamed polystyrene granule explosion; in turn, it creates condition for rapid ammonia nitrate decomposition within the chemical reaction zone.

Optimal mixtures of low-density *Es* have been developed to break thin ore deposits. The mixtures are applied depending upon the ore body geometry as well as geomechanical conditions of rock mass in the process of underground mineral mining. Volume percentage of the mixtures is as follows: 20-80 of the granulated ammonia nitrate; 80-20 of the granulated foamed polystyrene; 4.3-6.0 of diesel fuel (over 100%); 1.1-0.8 of sodium carboxymethyl cellulose (over 100%); and 3.0-4.0 of water (over 100%).

Relative efficiency of the mixed low-density *Es* depends upon the volume foamed polystyrene concentration; the efficiency can be identified through $A = -0.003p^2 + 0.0318p + 0.4883$ function.

It has been determined that to compare with standard industrial *Es*, the mixed low-density ones help perform wide range control (i.e. 35-160 MPa) of detonation velocity as well as pressure of blasting fumes either while charge density increasing or decreasing in the limit of 0.2-0.8 g/cm^3. In this regard, depending upon the charge density, value of the blasting fumes can be defined using $P = 92.529 \ln(\rho) + 174.05$ function.

The mixed low-density *Es* make it possible to control quantity of *Es* energy per unit volume of a blasthole through increase or decrease in the charge energy concentration according to changes in the rock mass resistivity or changes in physicomechanical characteristics of rocks and ores; moreover, the explosives improve blasting efficiency.

Empiric formula has been proposed to calculate specific consumption of the mixed low-density *Es* while thin ore deposit excavation under mining and geological conditions of Akbakay mine.

Ultimately, the research findings help develop flexible blasting procedures providing efficient explosive energy under variable characteristics of rocks, being disintegrated, for a wide range of ore bodies.

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Підбір оптимального складу та дослідження вибухових характеристик низькощільних сумішевих вибухових речовин, що використовуються для відбівання малопотужних рудних тіл

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Мета. Підбір оптимального складу сумішевої низькощільної вибухової речовини (ВР), що застосовується у вигляді свердловинних зарядів і забезпечуєть високу ефективність вибухових робіт при відпрацюванні малопотужних рудних покладів, за рахунок вивчення особливостей хімічного розкладання та газифікації пінополістиролу, ролі додаткових компонентів води та каталізатора у вигляді натрієвої солі карбоксіметилцелюлози й дослідження вибухових властивостей цих складів.

Методика. В даному дослідженні були проведені лабораторні експериментальні дослідження для встановлення ефективності застосування рекомендованих складів низькощільних ВР шляхом визначення основних вибухових характеристик зразків сумішевих ВР.

Результати. Розроблено оптимальний склад сумішевої низькощільної ВР, що складається з аміачної селітри, дизельного палива, гранульованого пінополістиролу, води та натрієвої солі карбоксіметилцелюлози для ефективного відбиваввння малопотужних рудних покладів, яка дає можливість у широких межах тиску регулювати швидкість детонації та величину. Визначено основні вибухові характеристики пропонованих складів низькощільних ВР, що дозволяють здійснювати вибухове навантаження масиву при гранично низьких значеннях енергетичних і детонаційних характеристик. Розроблений склад сумішевої низькощільної ВР дозволяє регулювати кількість енергії ВР в одиниці об'єму свердловини шляхом підвищення або зниження концентрації енергії заряду в міру зміни опірності масиву, тим самим забезпечує ефективне відбівання малопотужних рудних покладів з меншими показниками розбіжності.

Наукова новизна. Вперше виявлено залежність відносної працездатності сумішевих низькощільних ВР від об'ємного вмісту пінополістиролу, а також величини тиску газів вибуху від щільності заряджання.

Практична значимість полягає у створенні технологій для ведення вибухових робіт при відпрацюванні малопотужних рудних тіл на основі розробки оптимального складу низькощільних ВР, які відрізняються простотою, безпекою та ефективністю застосування, що дозволяє знизити собівартість видобування корисних копалин за рахунок зменшення ступеня розбіжності руди. Для умови рудника "Акбакай" запропоновано емпіричну формулу визначення питомої витрати низькощільної ВР.

Ключові слова: *гірський масив, рудні поклади, відбивання, видобуток, знебіднення, руда, вибухова речовина, щільність заряду*