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Determining the brisance of selected emulsion explosives used in mining via the Hess method
Określanie kruszności wybranych górniczych materiałów wybuchowych emulsyjnych przy użyciu próby Hessa

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Abstract: *Brisance, power and detonation velocity are the most important parameters describing secondary high explosives. They are determined by various methods. In the experimental determination of brisance, a number of different methods have been developed to date, including the Hess lead block compression test, plate dent test, sand test and the Kast method. The first method, which seems to be used most frequently, measures the deformation of a lead block caused by the detonation of an explosive sample. In this paper, the brisance of selected emulsion explosives used in mining, determined via the Hess compression test, are presented. Different emulsion explosives manufactured by Nitroerg S.A. were tested, including bulk and cartridged emulsions. Moreover, the properties of explosives were also predicted theoretically using dedicated software and the results correlated with those obtained from the test. In turn, theoretical values of brisance were calculated using the different approaches described in the literature.*

Streszczenie: *Kruszność, energia i prędkość detonacji są jednymi z najważniejszych parametrów opisujących materiały wybuchowe kruszące. Są one wyznaczane różnymi metodami. Do oznaczania kruszności materiałów wybuchowych opracowano do tej pory kilka metod badawczych, spośród których wymienić należy próbę zgniatania Hessa, test zagłębienia płytki, test piaskowy oraz metodę Kasta. Pierwsza metoda, która wydaje się być najczęściej stosowaną, odnosi się do odkształcenia walca ołowianego po detonacji próbki materiału wybuchowego. W artykule przedstawiono wyniki badań kruszności wybranych górniczych materiałów wybuchowych emulsyjnych przy użyciu próby odkształcenia Hessa. Analizie poddano różne materiały wybuchowe emulsyjne produkowane przez Nitroerg S.A., w tym luzem i nabojowane. Ponadto, przy użyciu dedykowanego oprogramowania wyznaczono teoretyczne parametry materiałów wybuchowych oraz skorelowano je z uzyskanymi wynikami kruszności. Z kolei teoretyczne wartości kruszności zostały obliczone przy użyciu różnych podejść, które opisane są w literaturze naukowej.*

Keywords: *explosives, brisance, Hess test*
Słowa kluczowe: *materiały wybuchowe, kruszność, próba Hessa*

1. Introduction

Detonation performance is fundamental in evaluating the power of high explosives. It may be determined using various small-scale methods and is characterized by detonation velocity, detonation pressure, detonation heat, specific kinetic energy, detonation products, working capacity etc. It describes the energetic (or working) capacity of an explosive i.e. its power, strength or energy [1, 2]. The working capacity is not expressed in work units but usually as the degree of compression of metal blocks, an increase in volume after explosion inside a lead block, the depth of the dent formed in a steel plate after explosion etc. [3]. It may also be expressed as a relative value in relation to a reference high explosive, such as RDX or TNT.
Brisance is one of the parameters used in defining the strength of an explosive. It is defined as the ability of an explosive to break rock or other objects. This means that it determines the effectiveness with which an explosive can fragment a rock or other object. The brisance of explosives is associated with the dynamic and rapid nature of the pressure wave at the detonation front. It mainly depends on the velocity of detonation – brisance increases with increases in detonation velocity. A very important issue in the field of explosive effectiveness is the precise determination of the interaction between the explosive and rock mass in mining, i.e. the crushing and propagation of blast-induced fractures in the rock in which explosive is fired [4, 5].
According to Doležal and Janda [6], the brisance of an explosive depends mainly on the density of the explosive, its velocity of detonation, the composition of gaseous products and the explosion temperature, and may be calculated from the Kast equation, which is as follows:

$$B = F \cdot \rho \cdot D \tag{1}$$

where: B – brisance [N/(m·s)], F – explosion force [J/kg], ρ – density of explosive [kg/m^3] and D – velocity of detonation [m/s].
Brisance and blasting capacity may be determined using the following methods:
– Trauzl lead block test [7, 8],
– underwater explosion test [9, 10],
– ballistic mortar test [11, 12],
– cylinder test [13, 14],
– Hess lead block compression test [15, 16],
– Kast test [17, 18],
– plate dent test [19, 20].

In the case of non-ideal explosives, the above methods do not always reflect the real power of the explosive since their detonation properties are difficult to measure due to the effects of physical, environmental and geometric factors on their detonation. This issue is particularly important in the case of chemically sensitized emulsion explosives. When preparing small samples for working capacity tests, the structure of such explosives may be damaged. This definitely influences the result of the test. It means that samples should be prepared (formed) with the greatest possible accuracy. Otherwise, results from the test may not be reliable.
The other problem which is mainly observed when testing the emulsion explosives, is that the samples in the most commonly used methods (lead block test, ballistic mortar, Kast test), are relatively small and, in many cases, should not be used for the testing of emulsion explosives. This is because the diameters of the tested charges are usually smaller than the critical diameter of the considered emulsion explosives. Thus the energetic capacity of emulsion explosives should be determined using those methods in which the sample diameters are closer to the critical diameter.

In fact, Keshavarz *et al*. [21] stated that the most convenient method for measuring brisance is the sand test or sand crushing test. They also mentioned that there is no reliable method for measuring brisance. Hence, they developed a novel, simple and reliable method, based on the elemental composition and molecular structure moieties. In the authors' opinion, no analytical method can provide more reliable results than experimental investigations. A novel method has also been developed by Vágenknecht *et al.* [22]. The basic principle is similar to the plate dent test and is associated with the creation of a crater in a heavy armor plate by the detonation of a hollow charge. Despite the fact that more than 25 years have passed from the development of this method, it has not been used extensively, so far.

Therefore, based on the authors experience, the Hess lead block compression test seems to be better suited for the testing of explosives, especially emulsion explosives, since the diameter of the tested samples is 40 mm. The greatest advantage of the Hess test, however, is that it may be used for in situ testing directly at the firing site, i.e. in both open pit and underground mines. Testing under such conditions is very beneficial, especially when testing bulk emulsions, because the samples may be collected directly from the mobile mixing-charging units. Thus, the same explosive as charged into the blastholes may be tested. The firing of such explosive samples out of the blastholes in Polish mining is possible based on the Regulation of the Minister for Energy from 22 February 2017 concerning the detailed requirements for the storage and use of blasting agents and blasting equipment in mining plant operations [23]. Based on this, the firing of explosives out of the blasthole is only permissible for research purposes and solely upon the consent of the mine operation manager.

In this paper, results of the brisance of selected emulsion explosives used in mining, determined via the Hess compression test, are presented. Various emulsion explosives manufactured by Nitroerg S.A. were tested, including bulk and cartridged emulsions. Additionally, the properties of these explosives were predicted theoretically using dedicated software and the different approaches described in scientific literature and correlated with the obtained brisance results.

2. Materials and methods

The object of the research were selected mining emulsion explosives, both bulk and cartridged, manufactured by Nitroerg S.A. including: Emulinit 2, Emulinit PM, Emulinit Strong, Emulinit GM1, Emulinit 8L and Emulinit 9L. All the tested packaged explosives were sensitized using glass microspheres at the manufacturing stage, except Emulinit GM1, which was sensitized chemically. The bulk emulsions in turn were sensitized chemically at the firing site using mixing-charging units. Selected parameters of the tested explosives, according to the technical data sheets, are presented in Table 1.

Table 1. Selected parameters of the tested explosives

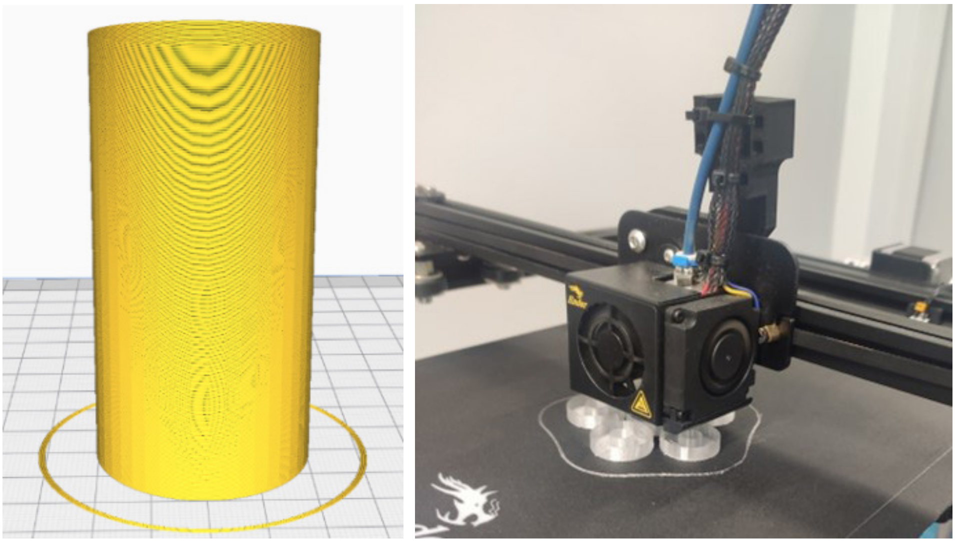
Explosive / Parameter	Emulinit					
	2	**PM**	**Strong**	**GM1**	**8L**	**9L**
D [m/s]	4,700	4,500	5,500	4,000	3,800	3,600
Friction sensitivity [N]	>360	>360	>360	>360	>360	>360
Impact sensitivity [J]	>25	>30	>30	>30	>30	>30
Specific energy [kJ/kg]	712	522	760	897	788	758
Gas volume [dm^3/kg]	854	767	870	904	870	918
Minimal diameter [mm]	≥32	≥32	≥40	≥32	≥34	≥45

Emulinit 2 and Emulinit Strong are intended for blasting operations in hard rock in underground and open-pit mines as well as for other engineering works such as tunneling carried out in dry and wet holes. Emulinit PM is a permitted explosive for coal dust and/or methane explosion hazard conditions. It can also be used for mechanical loading. Emulinit GM1 in turn is intended for use in underground and open-pit mines as a rock blasting explosive. Finally, Emulinit 8L and Emulinit 9L are bulk emulsion explosives produced

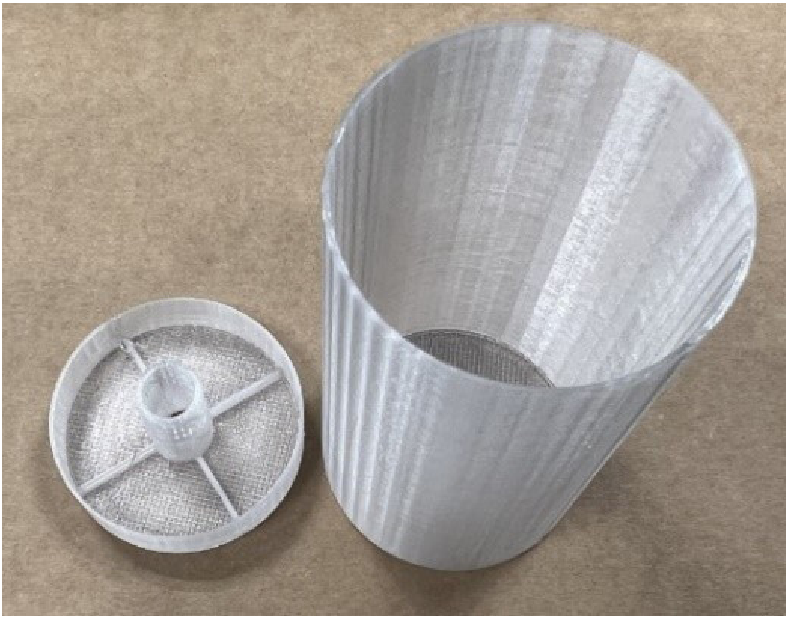
using mobile mixing-charging units, where 8L is dedicated for underground mines and 9L for open-pits.
Studies were carried out at Nitroerg S.A. company's test site in Bieruń, Poland. Samples were prepared by filling testing cups with explosives. In the case of packaged items, the relevant mass was determined using a laboratory balance prior to insertion into the testing caps. The sample was precisely formed in the cups using a glass rod to eliminate potential voids within the material. In the case of bulk emulsions, the components were blended manually for 30 s in 500 ml plastic cups using a glass rod before placing the relevant quantity into the test cups.
For the prediction of theoretical detonation parameters of the explosives under consideration, the EXPLO5 software (V6.06.02) provided by OZM Research s.r.o. was used [24].

2.1. Determination of brisance using the Hess test

Brisance of the explosives was determined using the lead block compression test, also known as the Hess method. The test procedure is described in the repealed national industry standard [25]. The principle of this method is calculation of the difference in the lead block height before and after detonation of the test sample. According to this standard, blocks should be casted with Pb1 category lead. The final dimensions of the blocks are 60 ±0.15 mm in height and 40 ±0.2 mm in diameter. The face surfaces should be machined to 10 grade. Cylindrical steel discs with a diameter of 41 ±0.2 mm and height of 10 ±0.2 mm, which serve as crushers, are placed between the explosive sample and lead block. The face surfaces of these discs were machined to 2.5 grade and hardened to 150-200 HB. The most difficult part of this method is the forming of the casing of the sample, which should be made from tarred paper, however the use of plastic casings is also allowed.
In this work, 99.97% purity cylindrical lead rods and 1.7035 steel discs were used. Plastic testing cups and rings with holders for detonators were 3D printed. The inner diameter of the cups was 40 mm and the height was 65 mm. A 50 g explosive sample was loaded into the cups.
The printout patterns were designed using FreeCAD and Ultimated Cura software. Printouts were made with a Creality Ender-5 Pro 3D printer (Figure 1). A polyethylene terephthalate glycol (PET-G) was used as a filament. The width of the print line was 0.4 mm and the height was 0.12 mm. The printing time of one measuring set was approximately 90 min.



(a) (b)



(c)

Figure 1. Designing the cups (a), 3D printing (b) and ready cup with holder (c)

For each test, a lead block was placed on a levelled steel base located on the ground. The crusher was then placed onto this block followed by the explosive sample on top of the test set, which was secured using electrical tape. Before firing, the holder with the fuse was pressed into the charge so that 10 mm of the blasting cap was recessed in the test explosive. Samples were initiated using a standard 0.65 g PETN fuse. The experimental setup and view of sample prior to firing is presented in Figure 2.
The change in the height of block due to axial compression is used as a measure of brisance. The method of measurement is described in detail in the above-mentioned standard. For this purpose, a calliper with an accuracy of at least 0.1 mm should be used. The height of the block needs to be measured at four points, as shown in Figure 3. The mean of the height (h_z) (in mm) is calculated using the following equation:

$$h_z = \frac{h_1+h_2+h_3+h_4}{4} \quad (2)$$

where: h_1, h_2, h_3, h_4 is the height of the block at the individual measuring points.
Compression of the lead block (Δh), i.e. the brisance of the explosive is calculated using the equation:

$$\Delta h = h_0 - h_z \text{ [mm]} \quad (3)$$

where: h_0 – is the original height of the lead block, h_z – is its height calculated from Equation 2. The value of h_0 in the follow-up measurements is 60 mm.

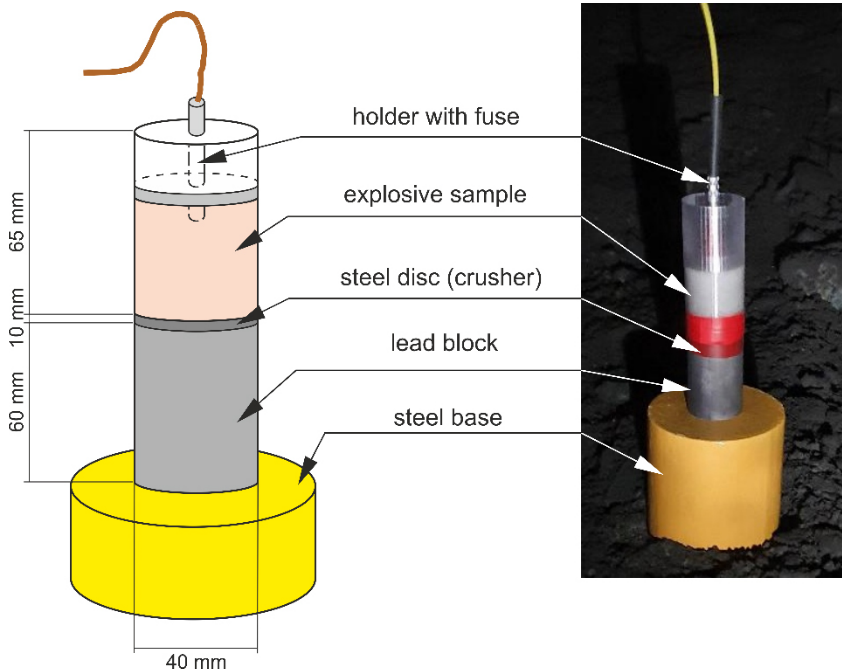


Figure 2. Scheme (left) and view of the sample prior to firing (right)

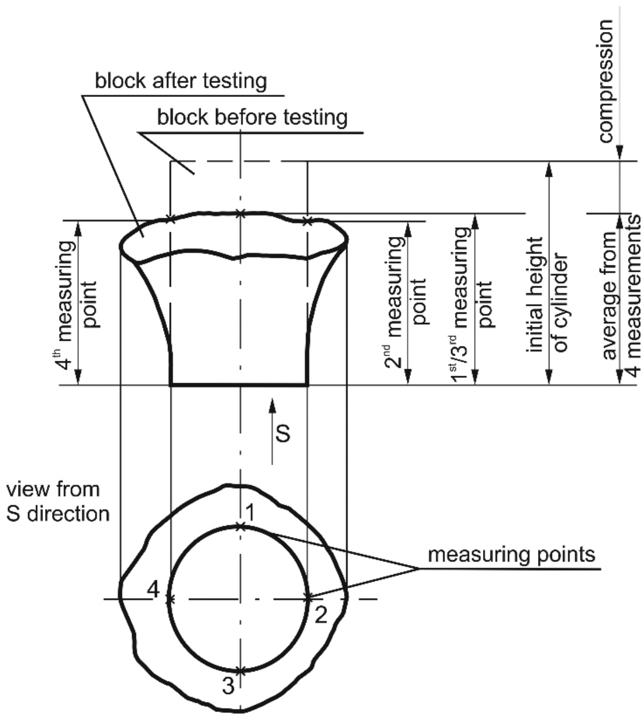


Figure 3. Measuring points for determining block height

According to the standard, brisance should be based on the results from three test samples per tested explosive, and the final value taken as the arithmetic mean. Results may be presented as brisance in mm or as a compression factor, in order to minimise the influence of lead compression changes due to the extent of crushing. The compression factor may be determined using the equation [26]:

$$\alpha = \frac{\Delta h}{h_0 - \Delta h} \tag{4}$$

where: Δh is the difference between heights of lead block before and after the test.

2.2. Prediction of theoretical properties of explosives

The theoretical detonation parameters were determined using EXPLO5 software, which is designed to predict detonation (detonation velocity, pressure, energy, heat and temperature) and combustion (specific impulse, force, pressure) performance of energetic materials. The determination of these parameters is based on a chemical equilibrium detonation model in a steady state. The equilibrium composition of both detonation and combustion products is calculated using a modified White, Johnson and Dantzig's free energy minimization technique [27]. The program applies the modified Becker-Kistiakowsky-Wilson and Exp-6 Equation of State (EOS) for gaseous detonation products, the ideal gas and virial equations of state of gaseous combustion products, and the Murnaghan EOS for condensed products [28]. The EXPLO5 software has been tested on a series of different types of explosives differing in composition and densities. It has been proved that there is an acceptable agreement between the calculated and experimental values of the detonation velocity and pressure [29]. Selected dialog boxes of the EXPLO5 software are presented in Figure 4.

However, the software does not allow the determination of brisance. Thus, theoretical values were calculated using two different approaches which are available in the scientific literature. Both approaches are based on a modified Kast equation. The first was presented by Elsharkawy and Fouda [30]. The explosion force in the proposed composition is the product of the number of moles of gaseous products, the universal gas constant and the temperature of explosion. Therefore, the Kast equation may be calculated using the equation:

$$B_{E-F} = n \cdot R \cdot T \cdot \rho \cdot D \quad \left[\frac{N}{m \cdot s}\right] \tag{5}$$

where: n – number of moles of gaseous products per 1 kg of the explosive, R – universal gas constant = 8.3145 J/(mol·K), T – detonation temperature [K].

Edwards and Palmer in turn presented a different approach [31] which additionally considers atmospheric pressure and the volume of gas created by the explosion. Brisance may be then calculated using the equation:

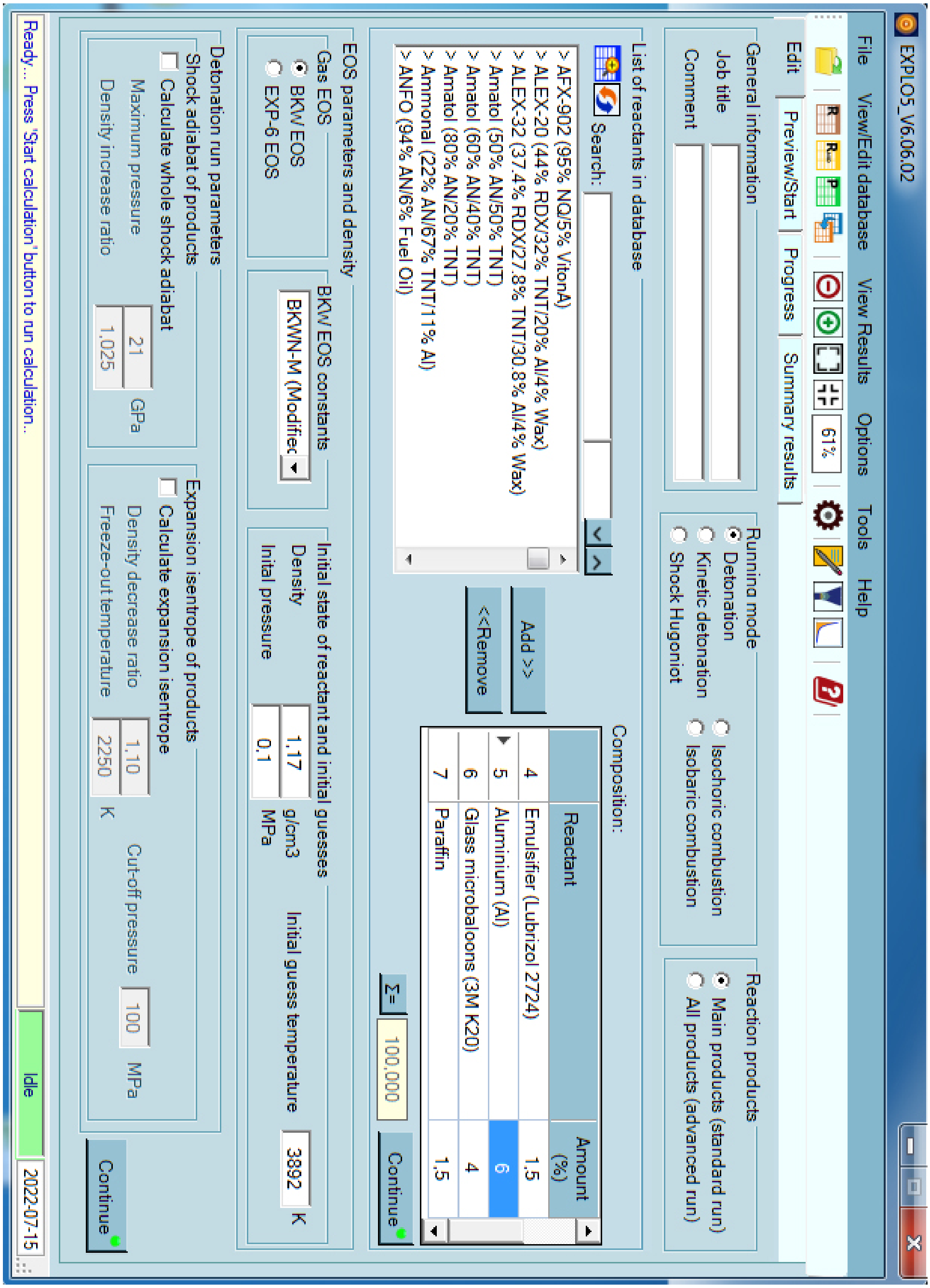
$$B_{E-P} = P_0 \cdot V \cdot \left(\frac{T}{273}\right) \cdot D \quad \left[\frac{N}{m \cdot s}\right] \tag{6}$$

where: P_0 – atmospheric pressure [N/m^2], V – volume of gas generated by the explosion and reduced to 273 K and 1 atm pressure.

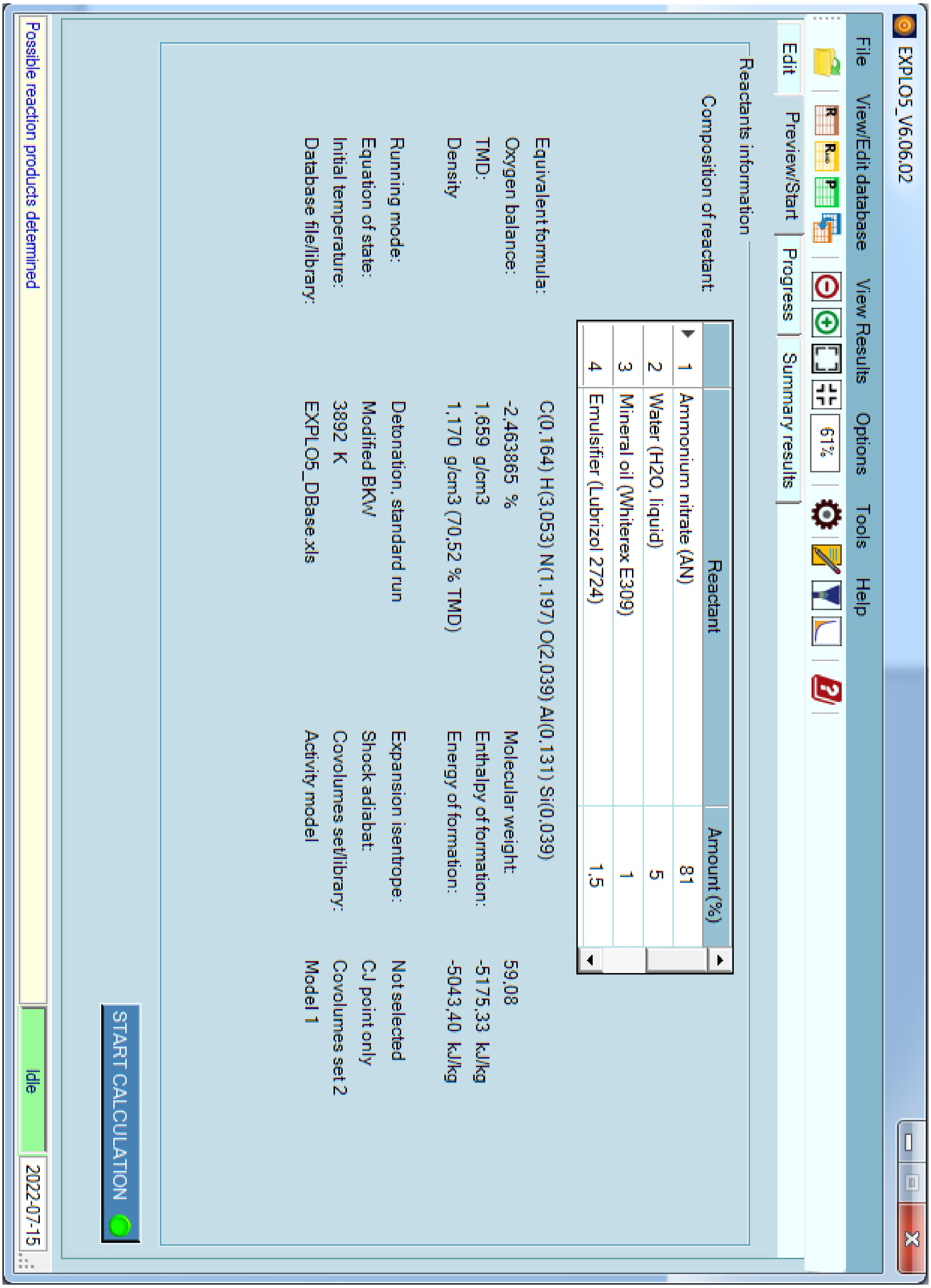
It is generally accepted that brisance is proportional to the impulse pressure, i.e. the impulse force acting on the surface unit of the partition (p_i). Therefore, brisance may be also estimated using the equation [32]:

$$p_i = \frac{1}{\gamma} \cdot \rho \cdot D^2 \quad [\text{GPa}] \tag{7}$$

where: γ – is the isentropic exponent in the Chapman-Jouguet plane.


EXPLO5_V6.06.02
File View/Edit database View Results Options Tools Help
61%
Edit Preview/Start Progress Summary results
General information
Job title
Comment
Running mode
Detonation
Kinetic detonation
Shock Hugoniot
Isochoric combustion
Isobaric combustion
Reaction products
Main products (standard run)
All products (advanced run)
List of reactants in database
Search:
> AFX-902 (95% NQ/5% VitonA)
> ALEX-20 (44% RDX/32% TNT/20% Al/4% Wax)
> ALEX-32 (37.4% RDX/27.8% TNT/30.8% Al/4% Wax)
> Amatol (50% AN/50% TNT)
> Amatol (60% AN/40% TNT)
> Amatol (80% AN/20% TNT)
> Ammonal (22% AN/67% TNT/11% Al)
> ANFO (94% AN/6% Fuel Oil)
Add >>
<<Remove
Composition:
Reactant
Amount (%)
4 Emulsifier (Lubrizol 2724) 1,5
5 Aluminium (Al) 6
6 Glass microbaloons (3M K20) 4
7 Paraffin 1,5
Σ= 100.000
Continue
EOS parameters and density
Gas EOS
BKW EOS
EXP-6 EOS
BKW EOS constants
BKWN-M (Modifiec
Initial state of reactant and initial guesses
Density 1,17 g/cm3
Initial pressure 0,1 MPa
Initial guess temperature 3892 K
Detonation run parameters
Shock adiabat of products
Calculate whole shock adiabat
Maximum pressure 21 GPa
Density increase ratio 1,025
Expansion isentrope of products
Calculate expansion isentrope
Density decrease ratio 1,10
Freeze-out temperature 2250 K
Cut-off pressure 100 MPa
Continue
Ready... Press 'Start calculation' button to run calculation...
Idle
2022-07-15

(a)


EXPLO5_V6.06.02
File View/Edit database View Results Options Tools Help
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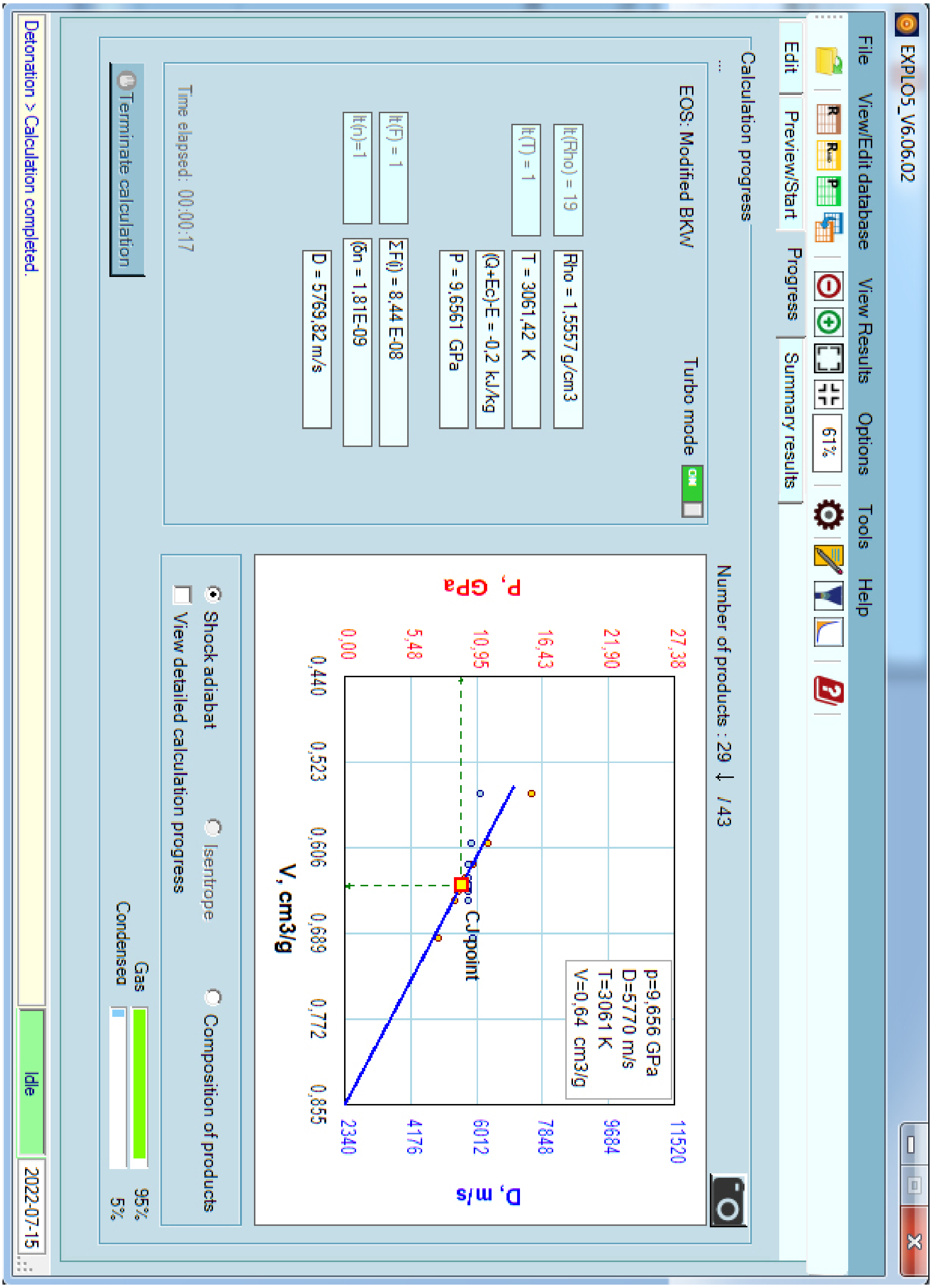
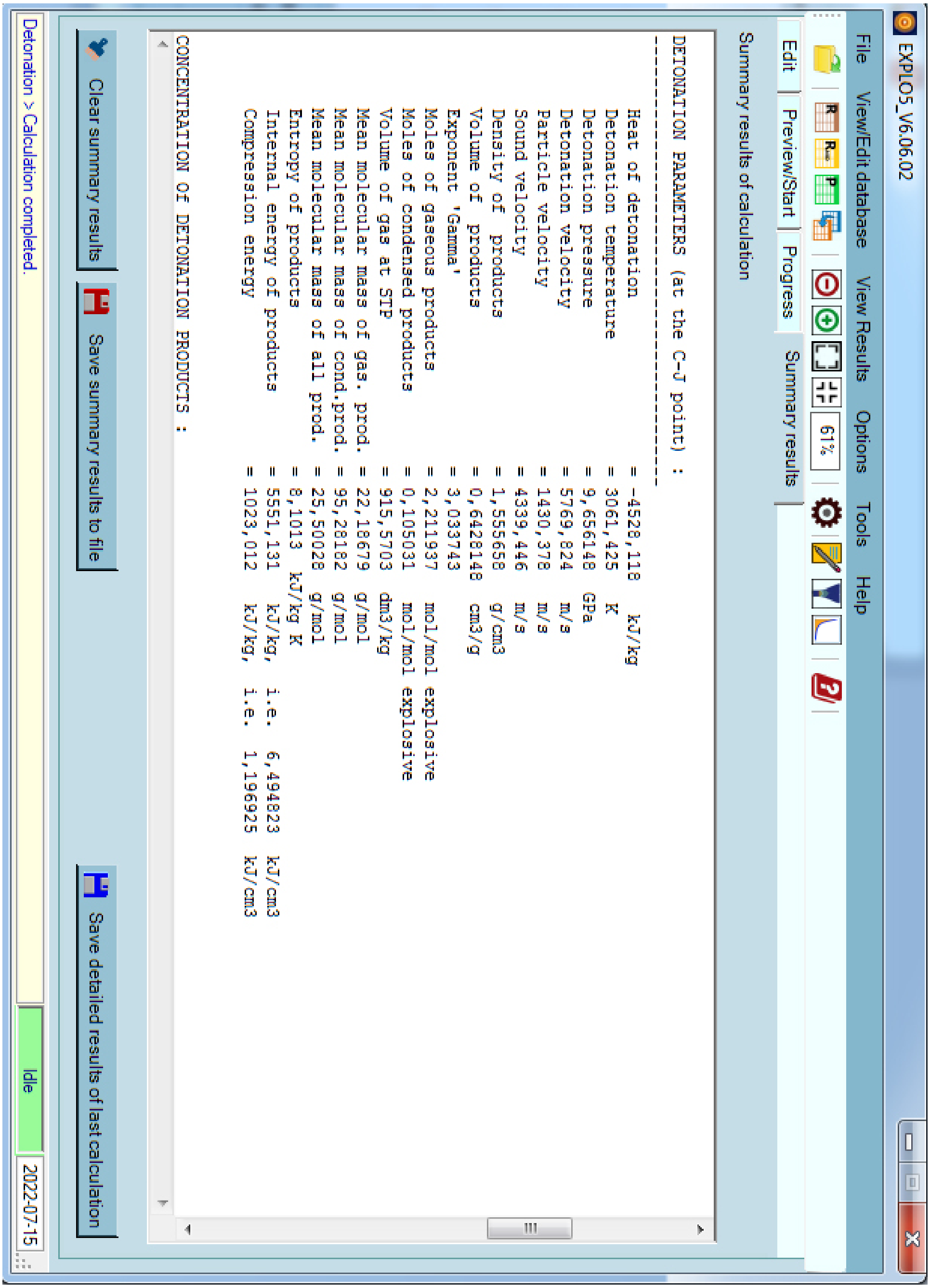
Edit Preview/Start Progress Summary results
Reactants information
Composition of reactant:
Reactant Amount (%)
1 Ammonium nitrate (AN) 81
2 Water (H2O, liquid) 5
3 Mineral oil (Whiterex E309) 1
4 Emulsifier (Lubrizol 2724) 1.5
Equivalent formula: C(0.164) H(3.053) N(1.197) O(2.039) Al(0.131) Si(0.039)
Oxygen balance: -2,463865 %
Molecular weight: 59,08
TMD: 1,659 g/cm3
Enthalpy of formation: -5175,33 kJ/kg
Density 1,170 g/cm3 (70,52 % TMD)
Energy of formation: -5043,40 kJ/kg
Running mode: Detonation, standard run
Expansion isentrope: Not selected
Equation of state: Modified BKW
Shock adiabat: CJ point only
Initial temperature: 3892 K
Covolumes set/library: Covolumes set 2
Database file/library: EXPLO5_DBase.xls
Activity model Model 1
START CALCULATION
Possible reaction products determined
Idle
2022-07-15

(b)


EXPLO5_V6.06.02
File View/Edit database View Results Options Tools Help
Edit Preview/Start Progress Summary results
Calculation progress
EOS: Modified BKW
Turbo mode
It(Rho) = 19
Rho = 1,5557 g/cm3
It(T) = 1
T = 3061,42 K
(Q+Ec)-E = -0,2 kJ/kg
P = 9,6561 GPa
It(F) = 1
ΣF(i) = 8,44 E-08
It(n)=1
(δn = 1,81E-09
D = 5769,82 m/s
Time elapsed: 00:00:17
Terminate calculation
Number of products : 29 / 43
p=9,656 GPa
D=5770 m/s
T=3061 K
V=0,64 cm3/g
CJ-point
P, GPa
D, m/s
V, cm3/g
Shock adiabat
Isentrope
Composition of products
View detailed calculation progress
Gas
Condensed
95%
5%
Detonation > Calculation completed.
Idle
2022-07-15

(c)



(d)

Figure 4. Selected dialog boxes of the EXPLO5 software

3. Results

3.1. Brisance

Results of experimental tests of the brisance were determined based on three samples being fired and are presented graphically as the compression of the lead block values measured in accordance with the standard and as calculated compression factors. Results are presented, without units, as a mean of three samples (Figures 5 and 6). Additionally, the uncertainty in the mean value of each result is shown on the graph.
The results indicate that the brisance is higher for packaged emulsions than for bulk emulsions, except for Emulinit GM1. This is probably because the structure of this explosive could be damaged during the preparation of samples. This is not the case for the other packaged emulsions, which are sensitized using glass microspheres. Thus, such sensitization does not affect the homogeneity of the explosive.

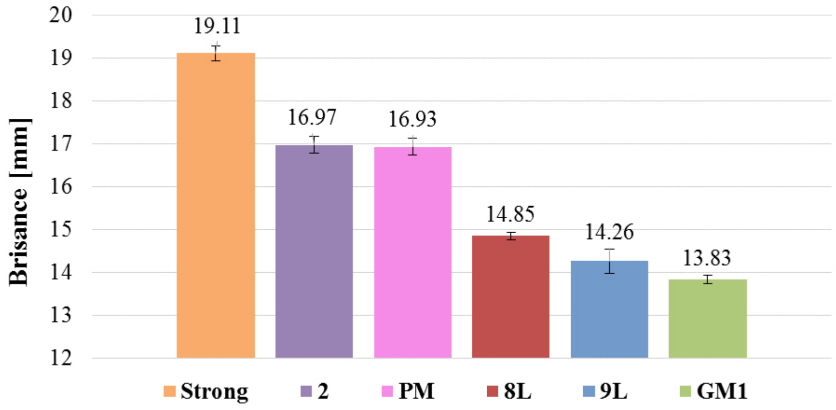


Figure 5. Results of brisance using the Hess method

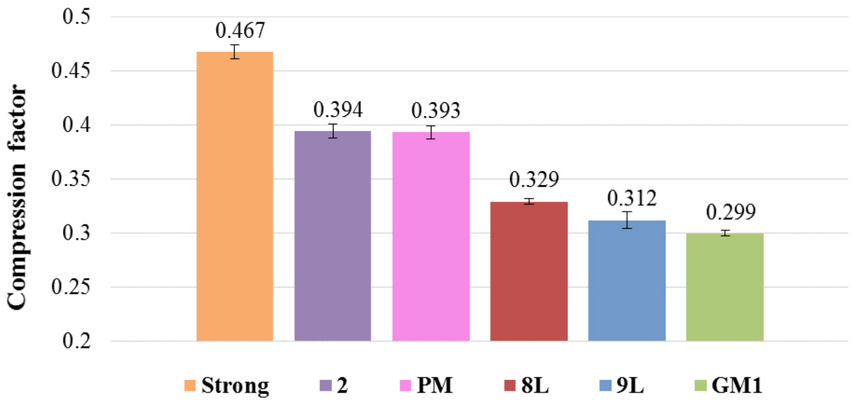


Figure 6. Compression factors for the tested emulsions

By excluding this explosive from further analysis, the brisance ranges from 14.26 mm for Emulinit 9L to 19.11 mm for Emulinit Strong, while the difference for both bulk emulsions is relatively small, i.e. only 0.59 mm, based on the mean values. However, dispersion in compression of the lead blocks for Emulinit 9L is relatively high. It may therefore be assumed, that the same compression levels were reached for both bulk explosives. Similar conclusions may be drawn from the graph of compression factors.

3.2. Theoretical properties of explosives

Theoretical properties of the explosives were determined using EXPLO5 software and a selection of them are shown in Table 2, including mean molecular mass of gaseous products, detonation temperature, volume of gas at standard temperature and pressure, heat of detonation, detonation pressure and compression energy. In this research, the Becker-Kistiakowsky-Wilson general gas equation, EOS of the condensed phase (incompressible) and equation of calculation method (minimization of free energy), were used.

Table 2. Selected parameters of the explosives calculated using the EXPLO5 software

Parameter \ Explosive	Emulinit					
	2	**PM**	**Strong**	**GM1**	**8L**	**9L**
Mean molecular mass of gaseous products [g/mol]	22.37	22.03	21.84	21.50	22.89	21.99
Velocity of detonation [m/s]	5,571	5,016	5,888	5,735	4,996	5,091
Detonation temperature [K]	2,586	1,974	2,353	2,649	2,284	2,185
Density*) [g/cm^3]	1.17	1.20	1.17	1.17	1.00	1.00
Volume of gas [dm^3/kg]	919	777	998	939	992	1020
Exponent gamma	3.10	3.32	3.14	3.08	2.97	3.18
Heat of detonation [kJ/kg]	3,564	2,393	3,216	3,776	2,869	2,863
Detonation pressure [GPa]	8.85	6.99	9.80	9.44	6.29	6.21
Specific energy [kJ/kg]	961	745	896	1024	830	826
Compression energy [kJ/kg]	921	674	1012	989	792	743

*) *value assumed for calculations*

Theoretical values of brisance were calculated using two approaches which are available in literature based on the modified Kast equation, according to Equations 5 and 6, but also estimated using the impulse pressure, according to Equation 7. For this purpose, theoretical parameters of explosives obtained using EXPLO5 were used, except for the detonation velocity whose values were based on experimental tests. This is because EXPLO5 assumes ideal detonation, so the theoretical and experimental values differ significantly. Since the calculated exponent of the explosives varies from 2.97 to 3.32, it was taken as being 3. Results are shown in Table 3.

Table 3. Measured and calculated values of brisance

Parameter \ Explosive	Emulinit					
	2	**PM**	**Strong**	**GM1**	**8L**	**9L**
Brisance via the Hess [mm]	16.97	16.93	19.14	13.83	14.85	14.26
Compression factor	0.394	0.393	0.467	0.299	0.329	0.312
Brisance by Elsharkawy and Fouda $\left[\left(\frac{N}{m \cdot s}\right) \cdot 10^{12}\right]$	5.29	4.11	5.66	4.79	3.15	2.97
Brisance by Edwards and Palmer $\left[\left(\frac{N}{m \cdot s}\right) \cdot 10^{12}\right]$	4.74	3.07	5.38	4.22	3.12	2.91
Brisance via the impulse pressure [GPa]	8.62	8.46	11.73	6.24	4.81	4.32

Results of theoretical calculations revealed that higher brisance was observed for packaged emulsions with the highest values being for Emulinit Strong and Emulinit 2. The lowest values, in turn, were for bulk emulsions, particularly for Emulinit 9L. Brisance calculated based on the modified Kast equation has shown the same order for the Emulinit Strong, Emulinit 2, Emulinit GM1 and Emulinit 9L. Minor differences are observed for estimations using impulse pressure, however Emulinit Strong, Emulinit 2 and Emulinit 9L are in the same positions.

4. Discussion

Due to the unreliable results obtained for Emulinit GM1, which was probably caused by breakdown of its structure while preparing the samples, it was excluded from further analysis. Results of brisance tests using the Hess method for the five remaining explosives show that both brisance and compression factors increase with increases in the nominal detonation velocity. This means that the higher velocity, the higher the brisance and compression of the lead block. The determined characteristics can be described using a linear regression. The calculated coefficients of determination, R^2, for both brisance and compression factor are greater than 0.99, which can be interpreted as a very strong and almost perfect correlation between brisance and detonation velocity. The relationship between the experimental brisance values and compression factor on the detonation velocity, is presented in Figure 7.

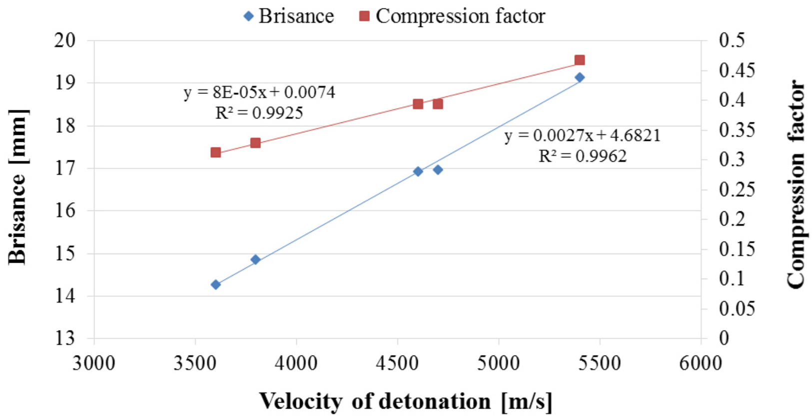


Figure 7. The relation between brisance, compression factor and detonation velocity

Results of theoretical calculations are presented in the form of relationships between the brisance determined based on the modified Kast equation (both approaches) and the compression factor from the experimental values (Figure 8) as well as the relationship between the impulse pressure estimation and compression factor (Figure 9). As with the analysis of experimental data, the Emulinit GM1 was excluded from further study.

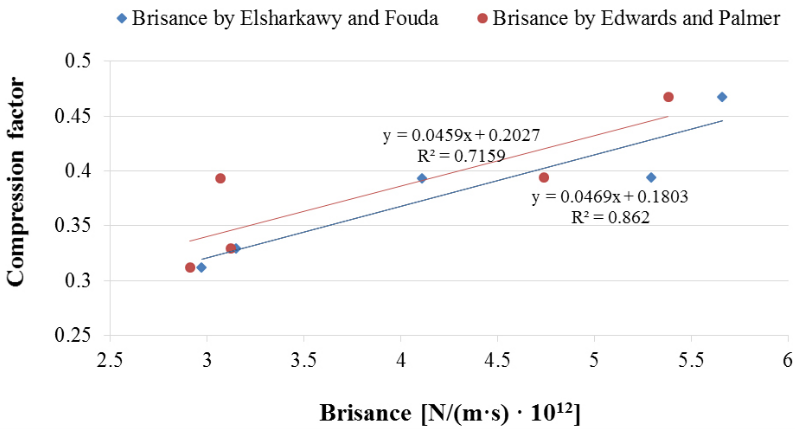


Figure 8. Relationship between theoretical brisance and experimental compression factor

Theoretical values of brisance, as per Edwards and Palmer, in relation to experimental compression factors, show that correlation between them is medium and slightly more than 70% of the data fitted to the regression model. A much better coefficient of determination was observed for the correlation of the theoretical brisance and compression, according to the equation proposed by Elsharkawy and Fouda which may be interpreted as strong (R^2 = 0.862). Finally, the theoretical brisance estimated using the impulse pressure, has been correlated with experimental compression factors, as shown in Figure 9.

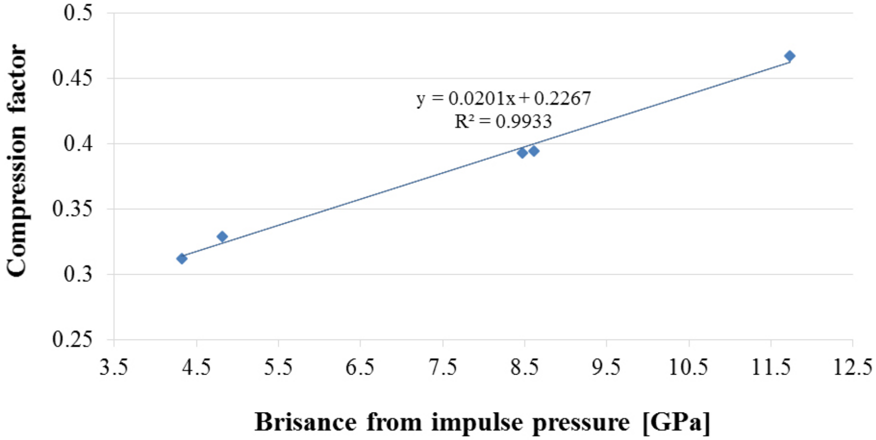


Figure 9. Relationship between theoretical brisance from impulse pressure and experimental compression factor

The estimated coefficient of determination between the brisance calculated using impulse pressure and compression factor has demonstrated a very strong and almost perfect correlation between those parameters (R^2 = 0.99). This means that the equation for the calculation of brisance using impulse pressure is very reliable with more that 99% of the data fitting the model. Such a high level of coefficient of determination allows an estimate of the detonation velocity to be made when experimental data of brisance are available. Thus, velocity of detonation may be determined based on the brisance tests indicating that the firing of large explosive samples is not necessary, since the modified Equation 7 in the following form, may be applied:

$$D = \sqrt{\frac{p_i \cdot \gamma}{\rho}} \quad \text{[m/s]} \tag{8}$$

To estimate the detonation velocity of the given explosives using Equation 8 and the linear relationship between the compression factor and the brisance determined based on the impulse pressure (as shown in Figure 9), the following equation can be applied:

$$D = 10^3 \cdot \sqrt{\frac{\left(\frac{\Delta h}{1.21-0.0201 \cdot \Delta h} - 11.3\right) \cdot \gamma}{\rho}} \quad \text{[m/s]} \tag{9}$$

The difference in the block height in Equation 9 is expressed in mm, while the density of the explosive in g/cm^3. It was also assumed that the isentropic exponent $\gamma = 3$. However, the equation given above may only be applied for emulsion explosives.

The presented experimental method, however, may only be used in determining the brisance of high explosives and is not suitable for less energetic explosives such as ANFO, since their critical diameter

is relatively close to the sample diameter. Nevertheless, the Hess method seems to be well matched for determining the brisance of different types of emulsion explosives, both bulk and packaged. The presented test results reveal high reliability of the method under consideration, which was confirmed by the low uncertainty of the mean values for each tested explosive. It should be emphasized that results of experimental tests were not referenced to those of the reference explosive. This is because the authors assumed that the reported method should be applicable directly at the firing site, i.e. in open pit and underground mines, where reference high explosives, such as TNT or RDX, cannot be used.
Considering the costs of measurements, attention should be paid to consumables, which include PET-G filament, lead blocks and steel crushers. The other costs, excluding labour, are related to 3D printing and the mechanical machining of both types of rollers. Thus, the total cost of consumables and their preparation per single test ranges from 40 € to 45 €.

5. Conclusions

- ♦ Experimental results of the lead block compression tests using the Hess method, have shown that this approach may be used successfully for determining the brisance of emulsion explosives used in mining. This is confirmed by the low uncertainty in the mean values for each tested explosive. It enables brisance to be determined with relatively low error.
- ♦ Analysis, both experimental and theoretical, confirmed that brisance is greater for packaged emulsions than for bulk emulsions. It also proved that the brisance of chemically sensitized packaged emulsion explosives cannot be determined via the Hess method, since the structure of such explosives may be damaged.
- ♦ Results have shown that brisance increases with increases in detonation velocity as indicated by the very strong and almost perfect correlation between those parameters. From the theoretical calculations, it can be concluded that the equation for calculating brisance via the impulse pressure, is very reliable, as confirmed by the high coefficient of determination between experimental and theoretical values. As a result, velocity of detonation may be calculated when the brisance is known. Taking into account all the studied theoretical approaches for brisance determination, it may be concluded that they give relatively good agreement with experimental results.
- ♦ The Hess method is a good alternative for determining the energetic capacity of explosives compared to other complicated, expensive and time-consuming methods. This is a very good comparative method for a specific batch of explosives. It is not complicated and gives reproducible results. However, it should be noted that ambient temperature affects the result. When measuring at different temperatures, a standard reference explosive such as TNT or RDX should be also tested in order to determine the real value of brisance.

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