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Research paper

Determination of the Equation of State for the Detonation Products of Emulsion Explosives

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Abstract: In this workcylinder testswere performed for two emulsion explosives (Emulinit 8L and Emulinit GM1) used in the mining industry. Based on the results of the tests, the detonation pressure and energy of these explosives were estimated. The detonation characteristics obtained, the profile of the expanding copper tube and the results of the numerical simulation enabled the constants in the JWL*(*Jones-Wilkins-Lee) equation of state to be determine for the detonation products of these two explosives.

Keywords: emulsion explosives, cylinder test, equation of state for detonation products

Nomenclature:

ANFO	Ammonium Nitrate – Fuel Oil
D	Detonation velocity [m/s]
EOS	Equation of State
JWL	Jones-Wilkins-Lee
ρ_0	Density [kg/m^3]

1 Introduction

The accuracy of computer simulations of fast-changing explosion processes, for example the impact compression of rock material and the formation of cracks, the acceleration and disruption of shells, and the compatibility of numerical simulations with real processes, depend in a significant way on the reality of the material data of the explosive systems and the rock mass. In particular, the correctness of an equation of state (EOS) assumed for the detonation products of an explosive is a very important factor.

The most popular equation of state used in numerical codes is the semi-empirical Jones-Wilkins-Lee (JWL) equation [1-3], which can be easily applied in numerical algorithms. It describes in a correct manner the behaviour of detonation products within the whole range of pressure changes and becomes an equation of an ideal gas for small densities. The JWL EOS for the detonation products of condensed explosives has the following form:

$$p = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \tag{1}$$

where $V = v/v_0$. The parameters p, v, and E denote pressure, specific volume and internal energy of the detonation products, respectively, v_0 being the specific volume of the explosive. This EOS was obtained from the expansion of internal energy in the neighborhood of the JWL isentrope of the detonation products in the form:

$$p = Ae^{-R_1 V} + Be^{-R_2 V} + CV^{(-1-\omega)} \tag{2}$$

The coefficients A, B, C, R_1, R_2 and ω (known as the JWL constants) are determined experimentally. The basic method for the determination of these constants is the so-called cylinder expansion test.

In the cylinder test, a metal tube is driven by the detonation products of a cylindrical explosive charge. The expansion of the tube is recorded by precise methods such as streak photography, X-ray photography or laser interferometry. The results of the cylinder test and the data obtained from modelling the process of driving the tube are the basis for determining the equation of state for the detonation products.

One of the first studies on the use of cylinder test results to characterize the properties of nonideal explosives was carried out in Poland [4]. Mixtures of ammonium nitrate with trinitrotoluene and aluminium powder were examined. The acceleration capability and the detonation energy of the explosives were estimated. Moreover, the equations of state for the detonation products were determined. The detonation and performance properties of five emulsion explosives containing glass microballoons were also studied experimentally and theoretically in [5]. The emulsion matrix was prepared using aqueous solutions of ammonium nitrate or its mixtures with sodium, calcium, nickel, and cobalt nitrates. The detonation velocity was measured and calculated, as well as ballistic mortar tests and cylinder tests were carried out for these explosives.

The large scale cylinder expansion test was applied in the Swedish Blasting Research Centre (Swebrec) to determine the work capacity of commercial explosives and the JWL EOS for the detonation products [6-8]. Among others, ANFO and certain emulsion explosives produced in Sweden were tested. The JWL EOS for these types of explosives were also obtained from cylinder expansion test measurements in Spain [9].

A review of the literature showed that the JWL equations for the detonation products of emulsion explosives produced in Sweden and Spain were determined in different ways using the results of cylinder expansion tests. The objective of the present work was to determine the JWL EOS for two commercial emulsion explosives produced in Poland by NITROERG S.A. The results of standard cylinder tests and numerical simulations carried out with our own computer programs were used for this goal. The mathematical model used in the codes and the method for the determination of the JWL coefficients are described in detail in papers [10, 11]. Additional data used in the codes are experimental characteristics of the explosives, such as the detonation velocity, pressure and energy obtained from the cylinder test data by the method given in [12, 13]. The JWL equations determined can be used to model phenomena accompanying the use of these explosives in a rock environment. Commonly known codes like LS DYNA can be used for this purpose.

2 Experimental

The emulsion explosives Emulinit 8L and Emulinit GM1 were tested. Emulinit 8L consists of a solution of oxidants (93 wt.%), an organic phase (7 wt.%) and a chemical modifier (3-5 wt.%) added at the final stage of production during elaboration. A matrix of Emulinit GM1 consists of a solution of oxidants (90 wt.%), an organic phase (6.5 wt.%) and aluminum powder (3.5 wt.%). The chemical modifier (0.1-0.5 wt.%) is also added during elaboration.

The explosives were contained in copper tubes (oxygen free copper Cu-DHP), which were hard drawn and annealing at a temperature of 800 °C. The tube was 300 mm in length, and its external diameter and wall thickness were 30.00 ±0.05 mm and 2.50 ±0.05 mm, respectively (Figure 1). Emulinit 8L was prepared in the laboratory by mixing the emulsion with sodium nitrate(III) ($NaNO_2$) in solution. The explosive thus prepared was loaded into the copper tubes. Emulinit GM1 was prepared by the manufacturer and loaded into sleeves made of thin foil placed in the tubes. In both cases, the excess of explosive formed due to gas evolution was removed. To initiate the detonation of the emulsion explosive, a detonator from phlegmatised RDX, weighing 5 g, was used. The charge shown in Figure 1 was place between the X-ray pulse and the film (Figure 2).

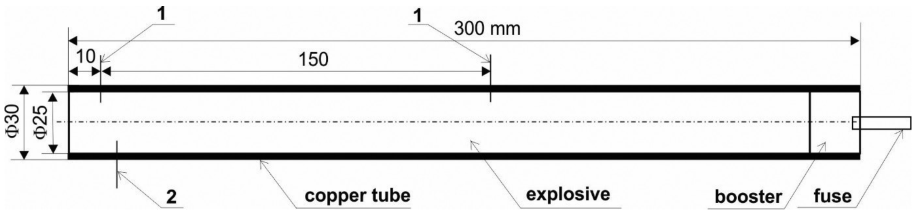

Figure 1. Diagram of the charge used in the cylinder test: 1 – sensors to measure detonation velocity, 2 – sensor triggering the X-ray pulse

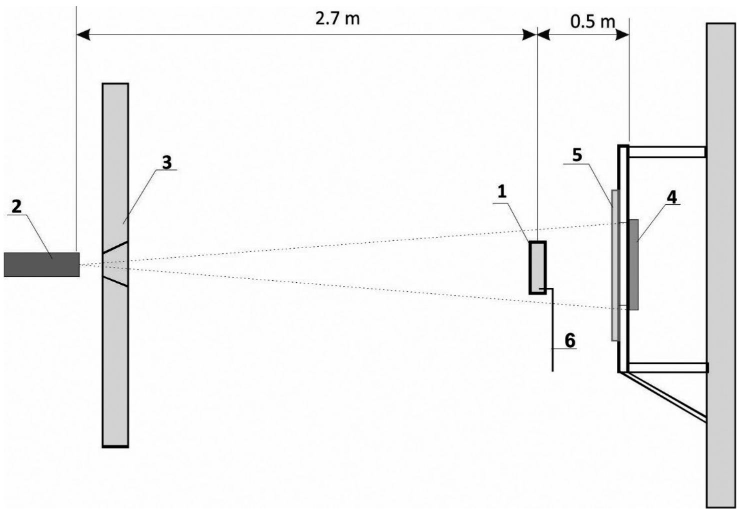

Figure 2. Arrangement for the cylinder test: 1 – copper tube with emulsion explosive, 2 – X-ray source, 3 – source shield, 4 – X-ray film, 5 – film shield, 6 – sensor triggering X-ray source

Two tests were performed for Emulinit 8L and three tests for Emulinit GM1. The density ρ_0 and detonation velocity D of the tested explosives are listed in Table 1. The measurement uncertainty in the case of the detonation velocity was ~1% (about 50 m/s for the tested explosives). This uncertainty results from the accuracy of measuring the distance between the sensors (1 mm). Radiographs of the copper tubes expanding under the effect of the detonation products are shown in Figures 3-7.

Table 1. Density and detonation velocity of the tested explosives

Explosive	Test number	ρ_0 [kg/m^3]	D [m/s]
Emulinit 8L	1	1130	4810
	2	1120	4920
Emulinit GM1	1	1140	failure
	2	1140	failure
	3	1170	4700

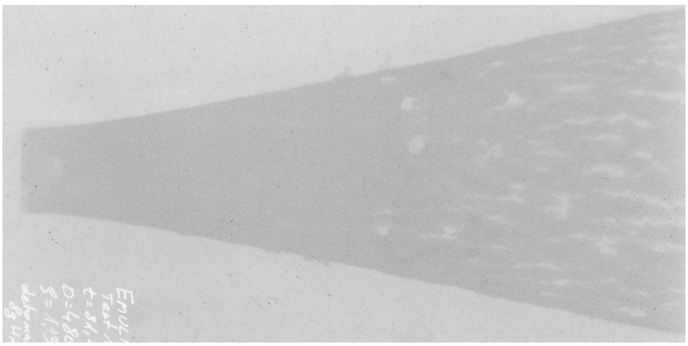

Figure 3. Inverse radiograph of the copper tube driven by the detonation products of Emulinit 8L (test 1)

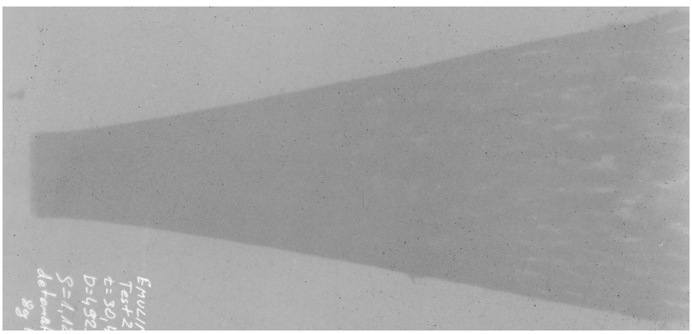

Figure 4. Inverse radiograph of the copper tube driven by the detonation products of Emulinit 8L (test 2)

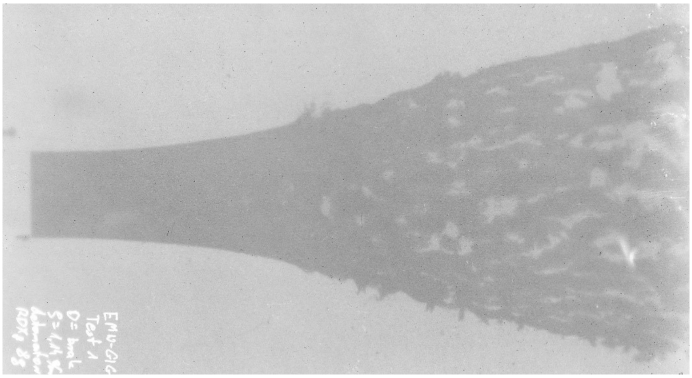

Figure 5. Inverse radiograph of the copper tube driven by the detonation products of Emulinit GM1 (test 1)

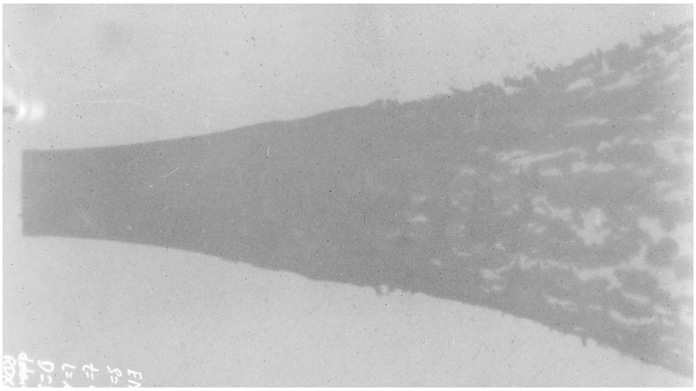

Figure 6. Inverse radiograph of the copper tube driven by the detonation products of Emulinit GM1 (test 2)

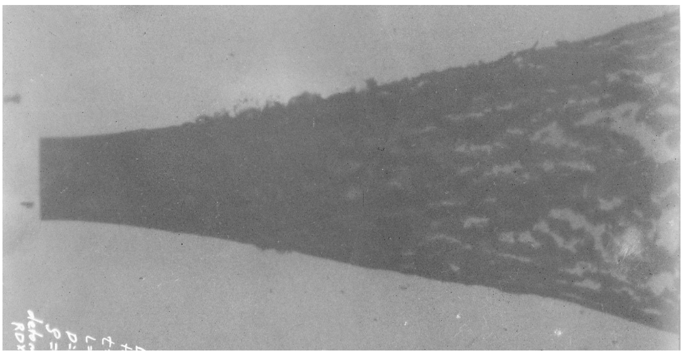

Figure 7. Inverse radiograph of the copper tube driven by the detonation products of Emulinit GM1 (test 3)

In the case of Emulinit GM1, only one test ended with a satisfactory result. This explosive was placed in the copper tubes by the manufacturer and, unfortunately, the uniformity of the charges was not good. The tube profiles obtained from tests 1-3 (Figures 5-7) are not smooth, which may indicate that the explosive was not homogeneous.

From the photographs for Emulinit 8L and Emulinit GM1 (test 3), the dependence of the external surface radius of the tube (r_e) on the axial co-ordinate x was determined using graphical programs (Figure 8). During the reading of the cursor position on the tube profile the micro-jet was omitted. Due to the blurring of the profiles, the accuracy of the external radius reading was approx. 0.1 mm.

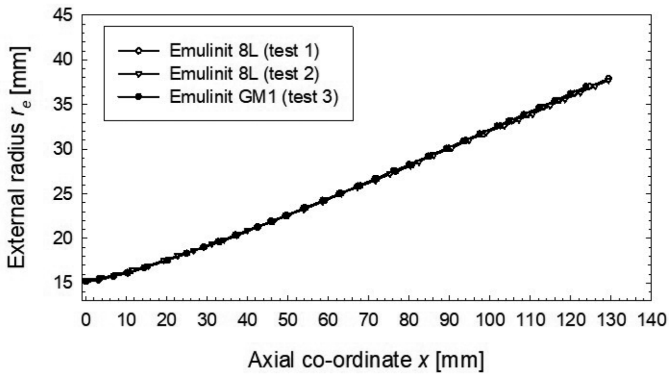

Figure 8. Radius of the external tube surface versus axial co-ordinate for the tested explosives

The dependences of the external radius on the axial axis and the detonation velocities are the results of cylinder tests for the explosives studied.

3 Determination of Detonation Parameters and Equations of State from the Cylinder Test

3.1 Tube velocity

According to the method described in [11], the results of the cylinder test and the detonation parameters such as detonation velocity, pressure and energy are necessary to determine the JWL coefficients. To find the γ-constant equation of state and the detonation pressure, the results of the cylinder test are used.

Moreover, the dependence of the tube velocity on the tube volume must be found to determine the detonation energy.

A detailed description of the procedure for determining the tube velocity using the cylinder test results is given in [12]. Firstly, the position of the central cylindrical surface of the tube (r_m) is determined from the tube profile by assuming the complete incompressibility of the tube material. Assuming that the motion of the detonation products and the tube material may be treated as a stationary one (which means that $x = D \cdot t$, where t – time), the dependence of the radius r_m on the axis co-ordinate can be changed to the dependence on time. The time dependence of the position of the tube's central surface is approximated by the appropriate function [12]. The radial velocity of the tube (u_m) can then be calculated by differentiating this function and finally the total velocity is expressed by the following equations:

$$u_L = 2D \sin\left(\frac{\theta}{2}\right), \qquad \theta = arctg\left(\frac{u_m}{D}\right) \tag{3}$$

Applying the experimental profiles of the expanding copper tubes (Figure 8) and the detonation velocities (Table 1), values of u_L were calculated as a function of time or of the tube relative volume (Figure 9).

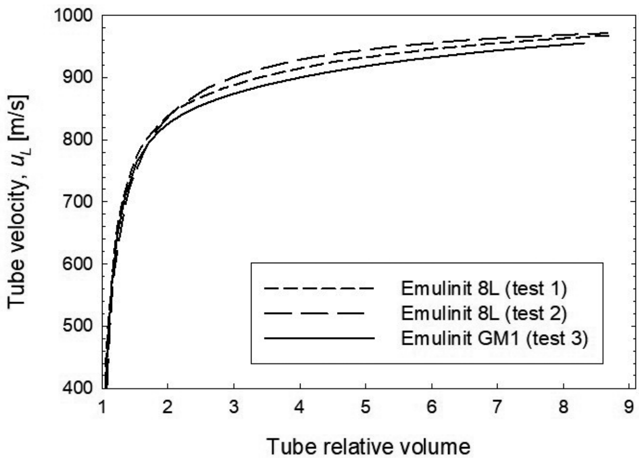

Figure 9. Dependence of the tube velocity on the tube relative volume for the tested explosives

The tube velocities for Emulinit 8L are higher than those for Emulinit GM1 due to the higher detonation velocity of the first explosive. Since the final velocities of the tubes in the two tests for Emulinit 8L differ slightly, the results of test 2, in which the higher detonation velocity was measured, were chosen for further consideration.

3.2 Detonation energy

The detonation energies E_0 of the emulsion explosives were obtained from the results of the cylinder tests by the method described in [12] and [14]. This energy is defined as the maximum work done by the detonation products during their expansion from the Chapman-Jouguet (CJ) point to infinite volume minus the shock compression energy [15]. As was shown in [12], a correlation exists between the detonation energy and the kinetic energy of the tube as follows:

$$\frac{E_0}{E_0^{st}} = \frac{\left(\mu+\frac{1}{2}\right)}{\left(\mu^{st}+\frac{1}{2}\right)}\left(\frac{u_L}{u_L^{st}}\right)^2 \tag{4}$$

where E_0 and E_0^{st} denote the detonation energies related to unit mass of the explosive tested and a standard (reference) explosive, respectively, and u_L and u_L^{st} are the velocities of the driven tubes determined for a relative volume of 10. The parameter μ is the ratio of the tube mass to the mass of the explosive. In order to estimate the detonation energy of the explosive tested, the emulsion-explosive EmEx sensitized by microballoons, with a density of 1.06 g/cm^3, was used as the reference explosive. Its detonation energy (E_0^{st} = 3330 J/g) was estimated in [16] on the basis of cylinder test results and thermochemical calculations.

The dependencies $u_L^2 = \phi(v_0/v)$ were approximated by straight lines and extrapolated to the relative volume of the detonation products, $v/v_0 = 10$, and the squares of the tube velocity for this volume were determined (Figure 10). By substituting the values obtained in this way in Equation 4, the detonation energies E_0 for the tested explosives were determined. Values of 3280 J/g and 3230 J/g were obtained for Emulinit 8L and Emulinit GM1, respectively.

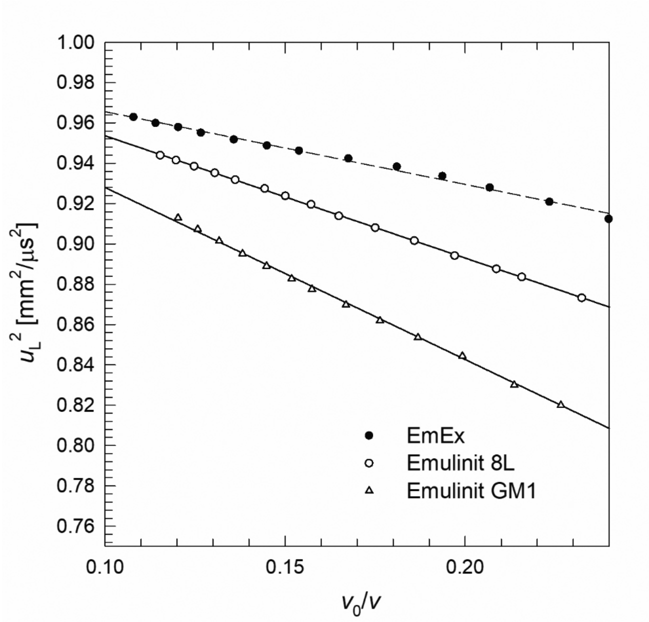

Figure 10. Dependence of the square of the velocity of the copper tube on the reciprocal volume of the detonation products

3.3 Detonation pressure

From the results of acylinder test, it is possible to roughly estimate the detonation pressure. An analysis of literature data for non-ideal explosives, Ref. [12] for example, shows that the inclination angle of the real isentrope of the detonation products, presented in the volume-pressure plane on a logarithmic scale, is close to the angle of the line representing the isentrope with a constant exponent γ, when the change in the relative volume of the products does not exceed a value of 3. The γ isentrope from the CJ point has the form:

$$p = p_{CJ}\left(\frac{v_{CJ}}{v}\right)^{\gamma} \quad (5)$$

The isentrope exponent designated for this interval of volume change was used to estimate the detonation pressure of the emulsion explosive according to the formula:

$$p_{CJ} = \frac{\rho_0 D^2}{\gamma+1} \quad (6)$$

The value of the exponent γ was determined by comparison of the experimental profile of the copper tube with that obtained from numerical modelling of the expansion process using the method described in [13], in which the properties of the detonation products are described by the γ-constant equation. The problem of driving the tube is solved numerically for a given value of the exponent γ and a discrete dependence of the external tube radius on the axial co-ordinate is derived. This dependence is interpolated by spline functions and the values of $r_{ej}(\gamma)$ at chosen points x_j ($j = 1, m$) are calculated. The exponent γ is determined by minimizing the function:

$$f(\gamma) = \sum_{j=1}^{m} \left[r_{ej} - r_{ej}(\gamma)\right]^2 \quad (7)$$

where r_{ej} is the experimental dependence obtained from the cylinder test. An exemplary comparison is shown in Figure 11.

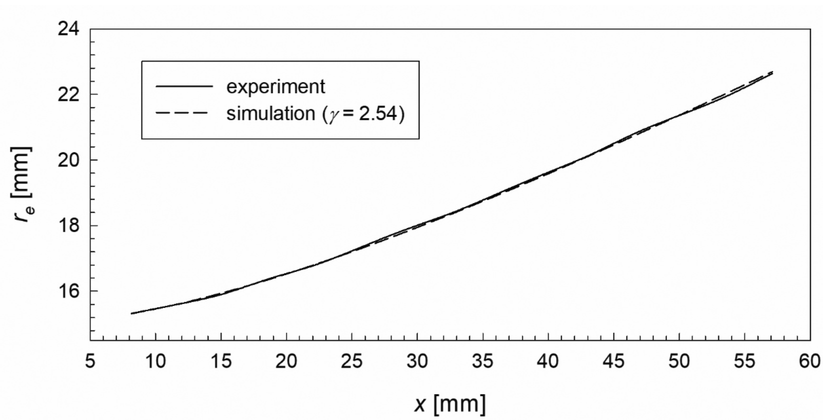

Figure 11. Experimental and calculated profiles of the copper tube driven by the detonation products of Emulinit 8L (γ-constant EOS)

The calculated values of the isentropic exponent were 2.64 and 2.59 for Emulinit 8L and Emulinit GM1, respectively. The detonation pressure calculated from Equation 5 was 7.4 GPa for Emulinit 8L and 7.2 GPa for Emulinit GM1.

3.4 JWL isentrope

Connections between the JWL constants can be established from the conservation laws written for the Chapman-Jouguet point. As a result, constants A, B, and C are expressed as functions of R_1, R_2, ω and ρ_0, D, p_{CJ} and E_0 [11].

Thus, only the constants R_1, R_2, and ω remain to be determined.

They are calculated by a method in which the experimental dependence of radial displacement of the external tube surface on the axial co-ordinate is compared with that obtained from a numerical simulation [11]. The mathematical model of the process of acceleration of the copper tube by the detonation products used in the computer simulation has been described in detail in [10]. The set of JWL constants is chosen for which the experimental and simulated displacements are sufficiently close to each other. The R_1, R_2, and ω are obtained from comparison of the experimental and calculated radial positions of the tube wall at chosen m values of the axial co-ordinate x_j. So, the values of these parameters are determined by minimizing the function:

$$f(R_1, R_2, \omega) = \sum_{j=1}^{m} \left[r_{ej} - r_{ej}(R_1, R_2, \omega)\right]^2 \tag{8}$$

where r_{ej} and $r_{ej}(R_1, R_2, \omega)$ are the experimental and calculated positions of the external surface of the tube, respectively. The comparisons are shown in Figures 12 and 13.

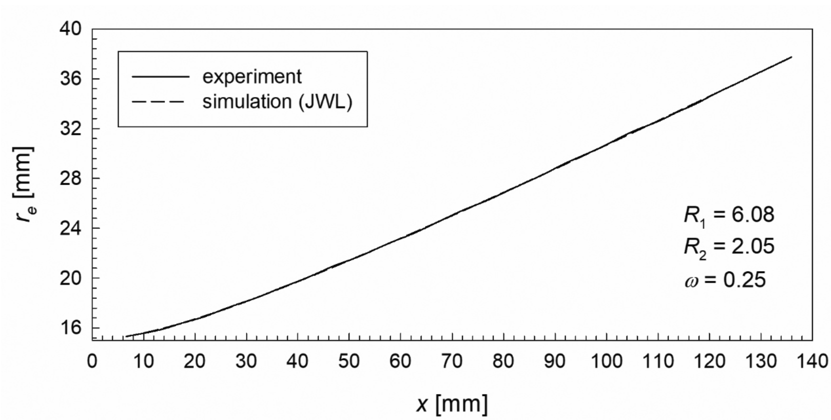

Figure 12. Experimental and calculated profiles of the copper tube driven by the detonation products of Emulinit 8L (JWL EOS)

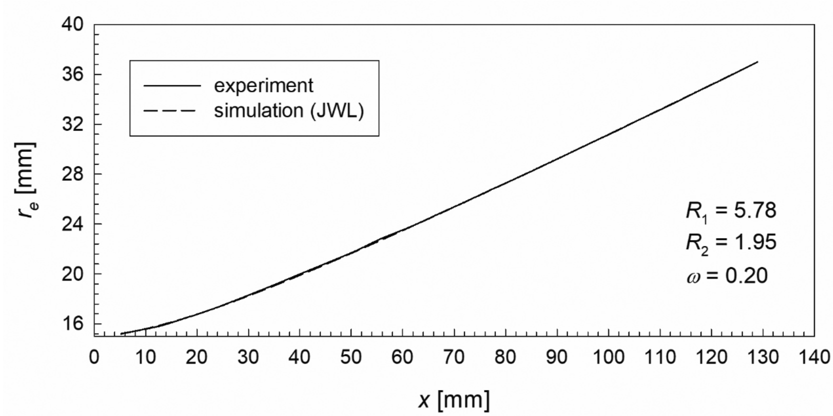

Figure 13. Experimental and calculated profiles of the copper tube driven by the detonation products of Emulinit GM1 (JWL EOS)

The JWL constants for the detonation products from both explosives tested are listed in Table 2. The detonation parameters of the emulsion explosives used in the determination of the JWL coefficients are summarized in Table 3.

Table 2. JWL constants for the detonation products of the tested explosives

Explosive	A [GPa]	B [GPa]	C [GPa]	R_1	R_2	ω
Emulinit 8L	252.20	15.566	0.5772	6.08	2.05	0.25
Emulinit GM1	202.84	13.726	0.4752	5.78	1.95	0.20

Table 3. Detonation parameters of the tested explosives

Explosive	ρ_0 [kg/m^3]	D [m/s]	p_{CJ} [GPa]	E_0 [GPa]
Emulinit 8L	1120	4920	7.4	3.7
Emulinit GM1	1170	4700	7.2	3.8

The JWL equation of the detonation products of Emulinit 8L was verified in [17], in which the LS DYNA code was used to model the process of driving the copper tube. Good compatibility of the experimental profile with the profile obtained from numerical simulation was obtained.

The JWL isentropes for the detonation products of Emulinit 8L and Emulinit GM1 are shown in Figure 14. These isentropes lie relatively close to each other (in a logarithmic scale). For a relative volume of up to approx. 30 ($\ln v/v_0 \sim 3.5$), the isentrope obtained for Emulinit 8L lies above the isentrope for Emulinit GM1; above this volume the relation is inverted.

The presence of aluminum powder in Emulinit GM1 may affect the mutual position of the expansion isentropes of the tested explosives.

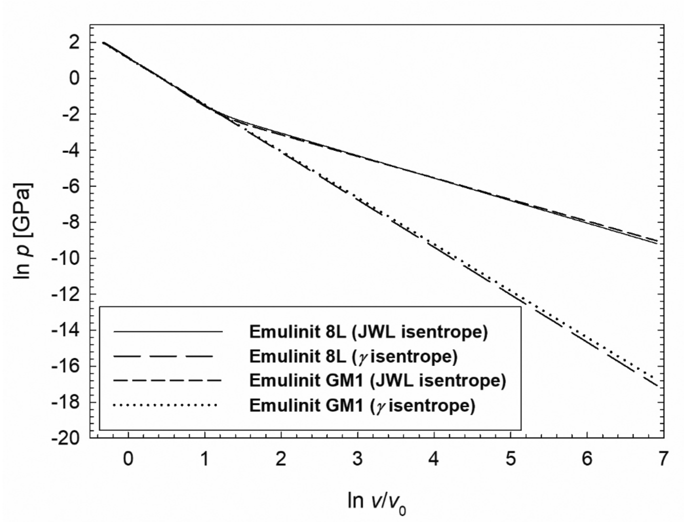

Figure 14. The JWL and γ isentropes for the detonation products of the explosives tested

Figure 14 also shows the γ-constant isentropes for the tested emulsion explosives. It is clearly visible how different the JWL and γ isentropes are. From the comparison, it follows that they give quite different values of pressure when the volume expansion ratio of the detonation products exceeds three and the differences increase considerably with increasing volume. While the final pressure values on the JWL isentropes in Figure 14 correspond to a pressure of ~10^5 Pa (~1 atm), this value at the γ isentropes is ~50 Pa. This shows conclusively that a proper form of the applied isentrope has crucial implications for the results of the simulation, especially when this simulation is performed for a lower pressure region.

4 Conclusions

Cylinder tests for the emulsion explosives Emulinit 8L and Emulinit GM1 were performed in this work. The results of these tests gave the profiles of the driven copper tubes and the detonation velocities. Based on these results, the changes in the velocity of tube with time were determined and the detonation pressure and energy were estimated. The detonation characteristics obtained, the profile of the expanding copper tube and the results of the numerical simulation enabled us to determine the constants of the JWL EOS for the detonation products of the tested emulsion explosives.

The equations of state can be used to calculate the expansion work performed by the detonation products of Emulinit 8L or Emulinit GM1, and they also enable researchers to simulate the propagation of shock and blast waves and their mutual interaction on the rock mass using professional codes.

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