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TESTING OF CONFINING PRESSURE IMPACTON EXPLOSION ENERGY OF EXPLOSIVE MATERIALS

BADANIA WPŁYWU CIŚNIENIA OKÓLNEGO NA ENERGIĘ WYBUCHU MATERIAŁÓW WYBUCHOWYCH

This paper presents the results of testing the explosion effectsof two explosive charges placed in an environment with specified values of confining pressure. The aim of this study is to determine the impact of variable environmental conditions on the suitability of particular explosives for their use in the prevention of natural hazards in hard coal mining. The research results will contribute to improving the efficiency of currently adopted technologies of natural hazard prevention and aid in raising the level of occupational safety. To carry out the subject matter measurements, a special test stand was constructed which allows the value of the initial pressure inside the chamber, which constitutes its integral part, to be altered before the detonation of the charge being tested. The obtained characteristics of the pressure changes during the explosion of the analysed charge helped to identify the work (energy) which was produced during the process.

The test results are a valuable source of information, opening up new possibilities for the use of explosives, the development of innovative solutions for the construction of explosive charges and their initiation.

Keywords: explosives, test stand, research methodology, explosion energy

Stosowanie techniki strzelniczej w profilaktyce tąpaniowej i metanowej polega na precyzyjnym niszczeniu określonych fragmentów górotworu, w których skumulowana jest energia sprężystości eksploatacyjnie odkształconych warstw sprężystych bądź nagromadzony jest metan. O skuteczności działania tego rodzaju zabiegów profilaktycznych decydują niszczące i penetrujące działanie gazów pod wysokim ciśnieniem uzyskanych w momencie przemiany wybuchowej materiałów wybuchowych w określonych warunkach środowiska. Ocena dynamiki przemiany wybuchowej górniczych materiałów wybuchowych jest przedmiotem badań w specjalnie do tego celu skonstruowanym stanowisku badawczym, gdzie istnieje możliwość zmiany warunków ciśnienia okólnego w otoczeniu badanego materiału poprzez zadawanie ciśnień porównywalnych do rzeczywistych w warunkach *in situ*.

Badanie polega na zdetonowaniu w komorze ładunku 10 g materiału wybuchowego (MW) przy pomocy zapalnika elektrycznego (ZE). Podczas badania mierzona jest wartość ciśnienia w komorze z częstotliwością próbkowania 1 MHz.

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W momencie dotarcia fali uderzeniowej do czujnika ciśnienia następuje nagłe zahamowanie jej propagacji powodujące znaczny wzrost ciśnienia, gęstości i temperatury, dające początek fali odbitej o odwrotnym kierunku (Onderka, 1998). Umożliwia to dokładną analizę rzeczywistego przyrostu ciśnienia w komorze badawczej.

Badania MW na przedstawionym stanowisku badawczym rozpoczęto w połowie 2014 roku. Wyniki badań dotyczą dwóch rodzajów MW – EMULINIT PM oraz METANIT SPECJALNY E7H produkcji Nitroerg S.A. Badania prowadzono przy ciśnieniu okólnym (wstępnym) w zakresie od 0 do 20 MPa. W artykule przedstawiono przebiegi ciśnienia w funkcji czasu z poszczególnych prób, na których widoczne są fale ciśnienia ulegające wytłumieniu według krzywych wykładniczych. Analiza przebiegów ciśnienia w funkcji czasu wskazała, że czas całkowitego wytłumienia pulsacji ciśnienia w kanale hydraulicznym czujnika ciśnienia wynosi około 4 ms. Przebiegi zarejestrowanych zmian ciśnienia podczas wybuchu ładunków obu MW dla różnych wartości ciśnienia wstępnego wskazują, że okres od chwili wybuchu do momentu całkowitego spadku ciśnienia pierwszego piku, zawiera się w przedziale od 137 do 280 µs.

Dla podanych przebiegów poszczególnych prób określono pracę (energię), jaka została wykonana przez ładunki MW. Wartość pracy obliczono jako tak zwany popęd jednostkowy (Maranda i in., 2010), rozumiany jako całka ciśnienia w funkcji czasu:

$$J_P = \int_0^t \Delta p dt$$

Otrzymane wyniki dla EMULINIT PM oraz dla METANIT SPECJALNY E7H wskazują, że istnieje rozrzut otrzymanych wartości J_P. W pierwszym przypadku wartość równoważnika pracy zawiera się w przedziale J_P = 0,00919÷0,00961 MPa×s, a dla drugiego materiału wynosi ona J_P = 0,00743÷0,01069 MPa×s, przy czym w obu przypadkach widoczna jest tendencja wzrostu tej wielkości wraz ze wzrostem ciśnienia wstępnego (okólnego). Wynika to z faktu, że wzrost ciśnienia wstępnego powoduje zwiększenie energii sprężystej całego układu hydraulicznego.

Analiza prędkości przyrostu ciśnienia dla obu MW (Rys. 9 i 10) wskazuje, że istnieje duży rozrzut poszczególnych wartości. Trudno więc określić jednoznaczną zależność pomiędzy prędkością przyrostu ciśnienia, a ciśnieniem wstępnym. Charakterystyczne jest jednak, że wartości prędkości przyrostu ciśnienia dla bardziej energetycznego materiału, jakim jest EMULINIT PM, są nieznacznie wyższe (V_p = 0,62÷1,6 MPa/µs), niż w przypadku METANITU SPECJALNEGO E7H (V_p = 0,39÷1,54 MPa/µs) czyli materiału o znacznie niższych parametrach, które go charakteryzują.

Uzyskane wyniki wstępnych badań są obiecujące i są kontynuowane dla innych rodzajów materiałów wybuchowych. Przedstawione prace otwierają nowe obszary badań środków strzałowych (materiałów palnych, pędnych i wybuchowych) dla opracowania nowych rodzajów ładunków oraz ich konstrukcji, co docelowo pozwoli zwiększyć efektywność działania ładunku MW w otworze wiertniczym i poprawi skuteczność stosowania metod profilaktyki tąpaniowej i metanowej.

Słowa kluczowe: materiały wybuchowe, stanowisko badawcze, metodologia badawcza, energia wybuchu

1. Introduction

Due to an upward trend in hard coal mining exploitation in the region of the Upper Silesian Coal Basin (about 10 meters per year), it has become necessary to rely upon resources located at greater depths. Currently, this depthis frequently exceeding the limit of 1000 m, which is related to conducting mining activities in conditions of increasing stresses, whilst experiencing the simultaneous increase in mining limitations and the growing risk of natural hazards, including: methane, rock burst, climate or caving hazards (Drzewiecki & Kabiesz, 2013; Krause, 2013). Measurements show (Hoek & Brown, 1980) that the values of horizontal stresses often deviate from the value of these stresses determined on the basis of the generalized Hooke's law. As can be observed from these measurements, the ratio of horizontal to vertical stresses, expressed as $k = p_x / p_z$, largely depends on the depth of the conducted research, i.e. the coefficient k increases with the depth increase, and therefore the values of horizontal stresses are greater. It has been proven that at large depths in the rock mass, a situation may occur when horizontal stresses are comparable with vertical stresses, i.e. hydrostatic state of stress will be produced. This means that it has become necessary to check the efficacy of using explosives which are used in the prevention of natural hazards in such conditions. For these reasons, studies aimed at determining the impact of complex environmental conditions on the performance characteristics of explosive charges have been initiated.

The use of blasting technology in rockburst and methane prevention involves the precise destruction of certain parts of the rock mass in which the energy is accumulated. This energy is formed during themining-induced deformation of elastic layers orlayers in which methane is accumulated. The performance efficiency of such prevention measures is due to chemical reaction, during which large amounts of heat and gases are emitted during the simultaneous concentration of energy in a very short time (Goc et al., 1999). The course of detonation for the same explosive is different, depending on the environmental conditions in which it is positioned.

The assessment of the dynamics of industrialexplosive detonation is the subject of research in a test chamber specifically constructed for this purpose. It enables the change of confining pressure p_W (initial) in the vicinity of the tested material through setting pressures so that they are comparable to actual underground mining conditions.The detonation of explosives causes a rapid rise of the pressure inside the test chamber and then its fall to a fixed pressure for a certain period of time.

These studies are intended to improve the efficiency and performance of methods of natural hazard prevention currently in use and in which the effects of explosive detonation are used (Myszkowski, 1996). The end result of these studies will be the construction of target-based explosive charges, which with decreased charge mass, should improve the expected performance efficiency.

During the tests, explosives resistance to water and high confining pressure was verified and the total energy of the shock wave and compressed gaseous products of the explosion were calculated (Hobler, 1982). The detonation of explosive chargeleads to mechanical work being necessary in the immediate vicinity of the blast hole, which is defined as the ability of explosives to perform the work. The work performed by an explosive charge depends on the amount of heat emitted and the number of gaseous moles of the explosion products, which in turn depends on the composition of the explosive. The limitation conditions of the medium in which the explosive charge is placed is also significant. There are a number of traditional methods for determining explosive performance efficiency, such as a ballistic pendulum or the Trauzl lead block test. Among more modern methods the following can also be included: a cylindrical test (Trzciński & Cudziło, 2001), an underwater test measuring the intensity of the blast wave (Maranda, 2008; Paszula et al., 2004; BS-EN 13763-23: 2004) and the Held test (Held, 2006). However, none of the aforementioned methods include changing the conditions of the environment, in which the analysed charge is located. When using explosive material for the prevention of natural hazards, knowledge of the changeable environmental conditions'effect on explosive performance is very important. Choosingen explosive, e.g. for rockburst prevention, with inappropriate parameters and poorly constructed charges may result in the increased risk of other natural hazards, such as fire, methane release or caving.

Determining the effect of confining pressure on the dynamics of the tested explosion material is important in the context of ever-increasing depths of coal mining. It also aims to discover for certain whether the explosive charges used in the mining industry, can perform efficiently in high hydrostatic pressure resulting from such significant depths. For these reasons, studies have been initiated and their preliminary results reported in this paper.

2. Research methodology

To determine the effect of changing confining pressure conditions p_w on an explosive charge and its work during the explosion, a test stand was constructed which allows this parameter to be changed in the vicinity of the charge.

2.1. Test stand

The test stand (Fig. 1), designed in GIG, whose main component is a chamber, where 10 g charge of explosive material is detonated by means of an electric detonator (ZE). This chamber allows the variable confining pressure of the fluid p_w to be set in the vicinity of the charge (Drzewiecki & Myszkowski, 2015). At the time that the shock wave reaches the pressure sensor, a sudden slowdown of its propagation takes places and this substantially raises the pressure, density and temperature, giving rise to a reflected wave in the opposite direction (Onderka, 1998). This enables a thorough analysis of the actual pressure increase in the test chamber.

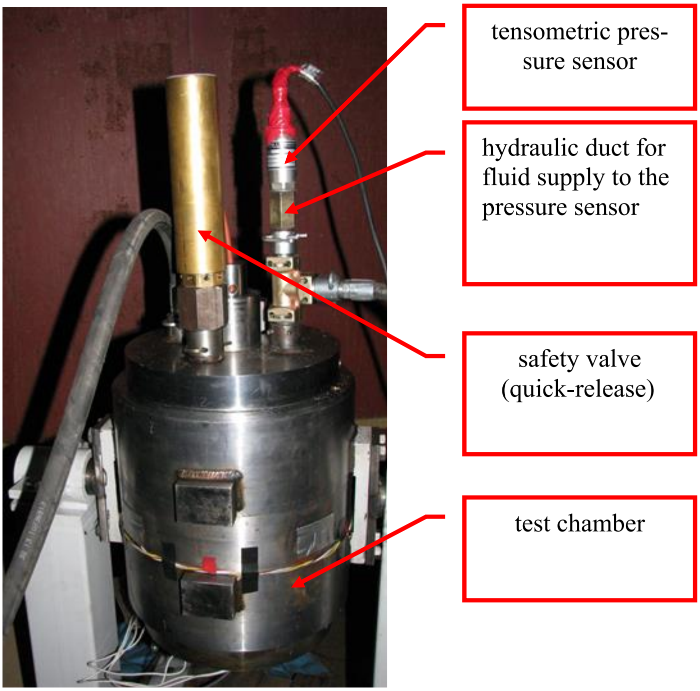

Fig. 1. Test chamber for explosives

In order to prevent the destruction of the test chamber, double protection was used by means of a quick-releasevalve (commonly used in hydraulic propsof powered roof support chocks) and fuse pressure in the form of a steel plate blanking the hole made in the bottom part of the chamber. The steel plate is the weakest mechanical element of the chamber and in the case of excessive internal pressure it is the first part to be damaged or destroyed, thereby preventing the chamber destruction, as it allows pressure to be released through the hole, protecting pressure sensor andthe elements providing power.

Other integral parts of the test stand are: a hydraulic pump with a maximum discharge pressure of 100 MPa and a delivery of 0.5 l/min, and a high-frequency set for recording test results in a digital form.

2.2. Characteristics of the explosives

Research concerning a number of explosives in the illustrated test stand began in mid-2014. The test results presented below refer to two forms of explosive – EMULINIT PM and METANIT SPECIAL E7H by Nitroerg S.A. (tested at a depth of 0.2 m; possible to be used in watered holes) (*http://www.nitroerg.pl*), initiated by the immediate pressure igniter ERGODET of 0.45A class, with a maximum hydrostatic pressure of operation equal to 9.8 MPa.

Table 1 shows the basic properties of the explosives used for the research, as provided by the manufacturer.

TABLE 1

Characteristics of the tested explosives

Material properties	**Explosive**	
	EMULINIT PM	**METANIT SPECJAL E7H**
Density, g/cm^3	1.15÷1.30	1.12 ±0.11
Detonation velocity, m/s	4500	1800
Oxygen balance, %	–8.53	4.4
Trauzl lead block distension, cm^3	170	160
Specific gas volume, dm^3/kg	767	580
Energy concentration, kJ/dm^3	2756	2260
Specific energy, kJ/kg	522	370

2.3. Measurement methodology

The HBM MGCplus measuring amplifier and a tensometric pressure sensor P3MBP BlueLine, with a measurement range of 500 MPa (class 0.2), were used for the measurement. An analogue signal was derived from the amplifier and then recorded by means of ameasuring card by National Instruments with a sampling frequency of 1 MHz. The first explosion attempts were initiated with ZK-300 M condensatory exploder, whose use resulted in impulse signal interference at the time of the explosion initiation. This was due to the fact that at the moment of impulse supply avoltage of above 800 V appeared on the terminals of the exploder, and this had a significant influence on the tensometric measurement results. This problem was removed by using a direct power source with a voltage of 9 V for further research, with which the electric detonator was initiated.

The accuracy of the method used, in which the sampling rate of 1 MHz (pressure measurements are made every 1 μs, with a resolution of 16 bit) is confirmed by the standard (PN-EN-13763-23:2004). This standard sets requirements for monitoring and recording, which should have an accuracy of ±1 μs, and ensures the correct measurement of the shock wave velocity.

Also, the experience of the Military Institute of Armament Technology (Dygdała et al., 2007; Kaczorowski et al., 2009) confirms that for the proper determination of detonation and shock wave velocity, measurement resolution in the range of 0.5÷2 μs is sufficient. The nature of the pressure curves obtained during the testing of explosives on the test stand, however, is different than in the cited reference literature, that is why a 10 ms recording time was chosen. The test results confirmed that this is asufficient amount of time to record the whole phenomenon.

3. Results and discussion

Test results of two types of explosives are shown below. The research involved the initiation of charges by means of an electric detonator and pressure measurement in the test chamber. The testing of the explosives was conducted with confining pressure p_w across a range from 0 to 20 MPa. Sample graphs illustrating the dynamics of pressure changes in the test chamber during the testing of explosives called: METANIT SPECJAL E7H are presented in Fig. 2 and EMULINIT PM in Fig. 3.

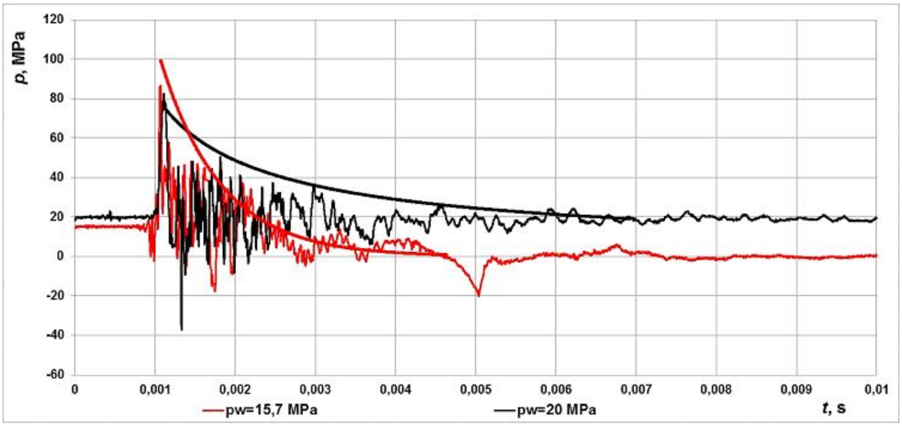

Fig. 2. Pressure waveforms as a function of time $p = f(t)$ in the test chamber during the testing of METANIT SPECJAL E7H

As shown in two waveforms (Fig. 2) representing the attempts at different confining pressure, the pressure wave is subjected to dampening along the exponential curve, which results in the settling time of the pressure in the chamber.

A similar phenomena can also be observed in Fig. 3, where during the testing of EMULINIT PM at p_w = 10 MPa, fuse pressure was activated which resulted in a rapid decrease in the pressure time. Slower pressure drop in time is characteristic for an attempt at p_w = 5.6 MPa.

As shown in Fig. 2 and 3, pressure waveforms as a function of time indicate that the timeof the total dampening of pressure fluctuation in the test chamber is about 4 ms, while during the operation of the pressure fuse, the dampening time occurs for up to approximately 1.5 ms.

The measurement system is versatile with regard to the range of sampling frequencies from a few Hz to 1 MHz, and the maximum recording time depends only on the capacity of the hard

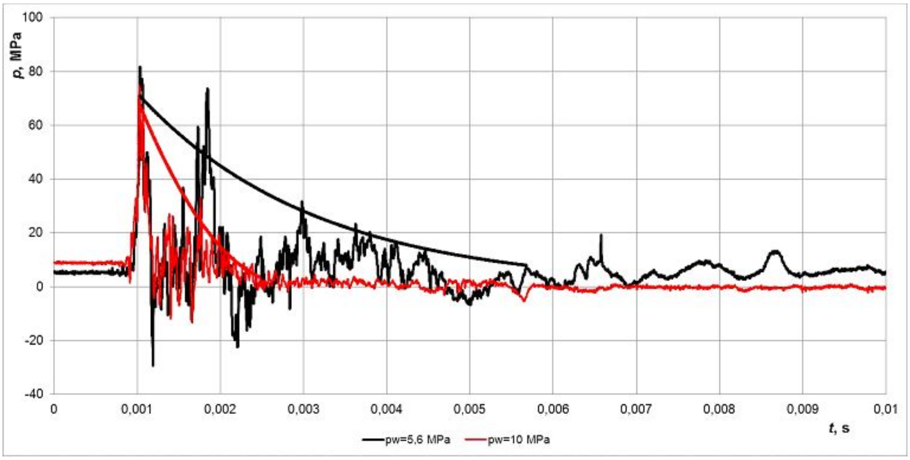

Fig. 3. Pressure waveforms as a function of time $p = f(t)$ in the test chamber during testing with EMULINT PM

disk of the computer. These parameters are indicative of a measuring system's suitability for the study of combustion dynamics, for both of the explosives studied, as well as gas-generators or rocket fuels characterized by lower combustion dynamics.

In order to verify the measurement apparatus used in the study, spectral analysis of pressure signals was conducted based on the Fourier transform FFT, an example of which is shown in Fig. 4.

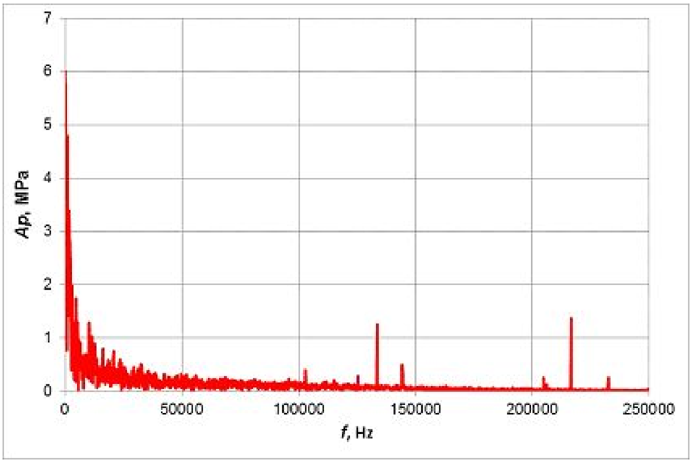

Fig. 4. Exemplary power spectrum of the pressure determined during an attempt in the test chamber

It confirms that the main part of the power spectrum of the pressure signal is within approximately 100 kHz of the frequency responseand this is sufficient for the testing of explosives and pyrotechnics.

Further analysis focused on the first pressure increase peak caused by the detonation of explosive, which is the most characteristic part of the waveform (Maranada et al., 2010). The first peak has the highest instantaneous value of pressure and reflects the properties of the shock wave during the detonation of explosive material initiated with an electric igniter. Other recorded instantaneous pressure values depend on many factors related to, for example, reflection and the interference of the shock wave.

Waveforms of the registered pressure changes (Fig. 5 and 6) during the explosion of both explosive charges for various values of the confining pressure indicate that the period from the moment of explosion until the total pressure drop of the first peak, is within a range of 137 to 280 μs. The volatility of the pressure value charts for various sizes of confining pressure is characteristic. One particularly striking difference can be seen for the two measurements of METANIT SPECJAL E7H charge at 20 MPa confining pressure, where the value of the maximum pressure in both cases is about 80 MPa, while the rate of pressure increase and the duration of the phenomenon differ significantly.

It should be highlighted that the tested explosives are characterized by a significant difference between their characteristic properties, as shown in Table 1 (for example, the detonation speed for EMULINIT PM is 4500 m/s, and METANIT SPECJAL E7H 1800 m/s).

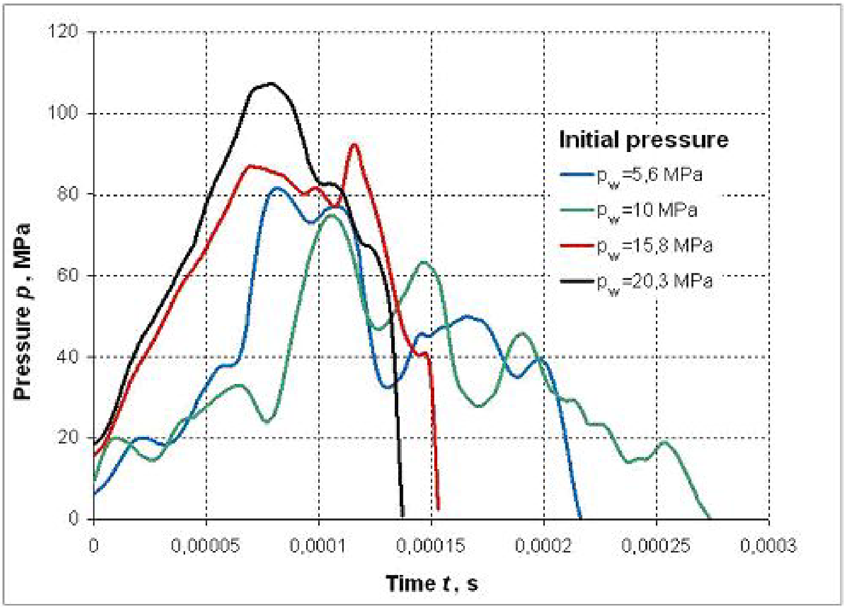

Fig. 5. Registered characteristics of pressure changes during the explosion of a 10 g charge of EMULINIT PM for different confining pressures

Due to the fact that the obtained pressure change results are highly volatile, which may be affected by such factors as: the construction and location of each charge of explosive material with the power igniter and the location of the pressure sensor at the end of the hydraulic ductconnected to the test chamber. Due to the fact that, the test chamber is a closed system,the

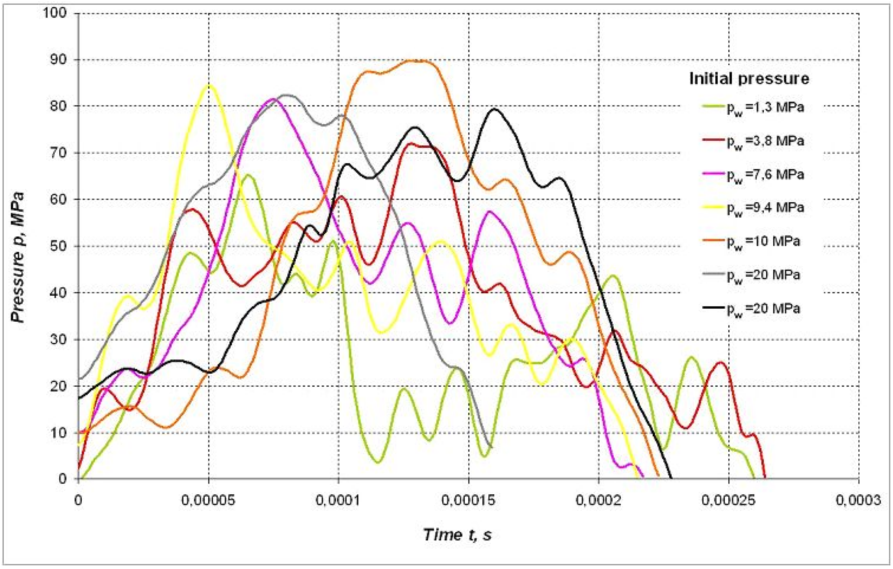

Fig. 6. Registered characteristics of pressure changes changes during the explosion of a 10 g charge of METANIT SPECIAL E7H for different confining pressures

propagating shock waves are subject to multiplied reflection and refraction at the edges of the inlet to the hydraulic duct connecting the chamber with the hydraulic pressure sensor. This can cause interference of the waves recorded by the sensor. Therefore, for the specified waveforms of individual attempts, the work (energy) produced by explosive charges was determined. The work value was calculated as the so-called unit impulse (Maranda et al., 2010), understood as the integral of the pressure as a function of time:

$$J_P = \int_0^t \Delta p dt$$

The results obtained for EMULINIT PM (Fig. 7) and for METANIT SPECJAL E7H (Fig. 8) indicate that there is a dispersion of the obtained J_P values. In the case of the former, the equivalent of work value is within a range of $J_P = 0.00919 \div 0.00961$ MPa×s, and for the latter it is within $J_P = 0.00743 \div 0.01069$ MPa×s. In both cases there is a visible growth tendency of this magnitude with the increasing confining (initial) pressure p_w. This is due to the fact that an increase in confining pressure causes an increase in the confining elastic energy of the whole hydraulic system.

The analysis of pressure increase rate for both explosives (Fig. 9 and 10) indicates that there is a large dispersion of individual values. It is therefore difficult to determine, unambiguously, the relationship between the rate of pressure increase and the confining pressure. However, it is characteristic that the pressure increase rate for material of higher energy value, i.e. EMULINIT PM, are slightly higher ($V_p = 0.62 \div 1.6$ MPa/μs) than in the case of METANIT SPECJAL E7H ($V_p = 0{,}39 \div 1.54$ MPa/μs), a material that has significantly lower parameters. However, it should be noted that the pressure increase rates are characterized by a significant dispersion, resulting possibly from shock wave propagation in the test chamber.

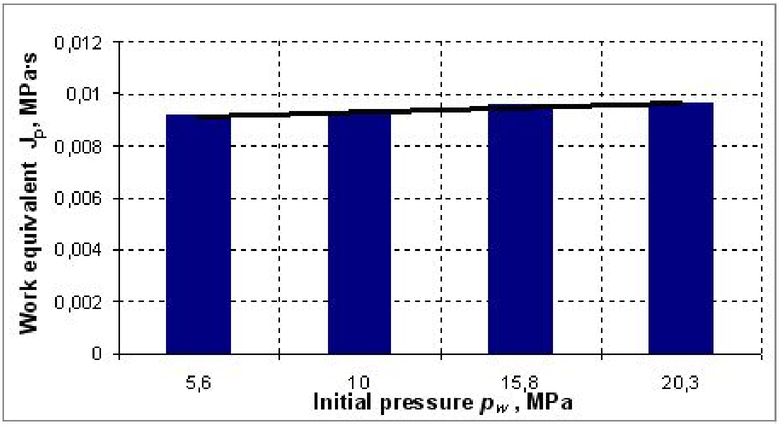

Fig. 7. Calculated values of work equivalent duringthe explosion of a 10 g charge of EMULINIT PM for different confining pressures

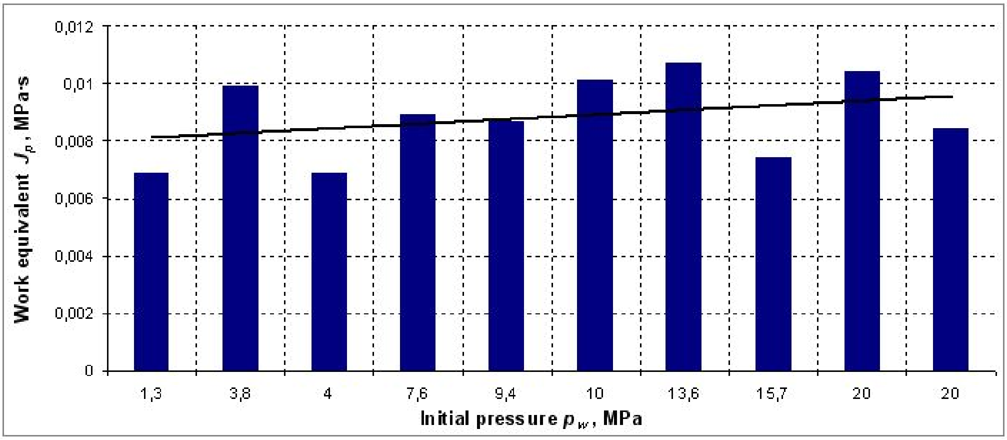

Fig. 8. Calculated values of work equivalent duringthe explosion of a10 g charge of METANIT SPECJAL E7H for different confining pressures

4. Conclusions

The results presented form the initial stage of research undertaken in mid-2014. The aim of this study is to determine the effect of changing pressure conditions in the vicinity of explosives on the produced work (energy) in the form of surface integral equivalent under the pressure curverecorded during the explosion. At the same time, the rate of pressure rise inside the chamber was analysed for both explosives.

Adopting this type of research required the design and construction of a special test stand, whose main element is a test chamber (Fig. 1). This stand was successfully modified during the course of this research. Inside the test chamber it is possible to increase the size of confining hydrostatic pressure to adesired value. Under such conditions, the charge being tested was placed

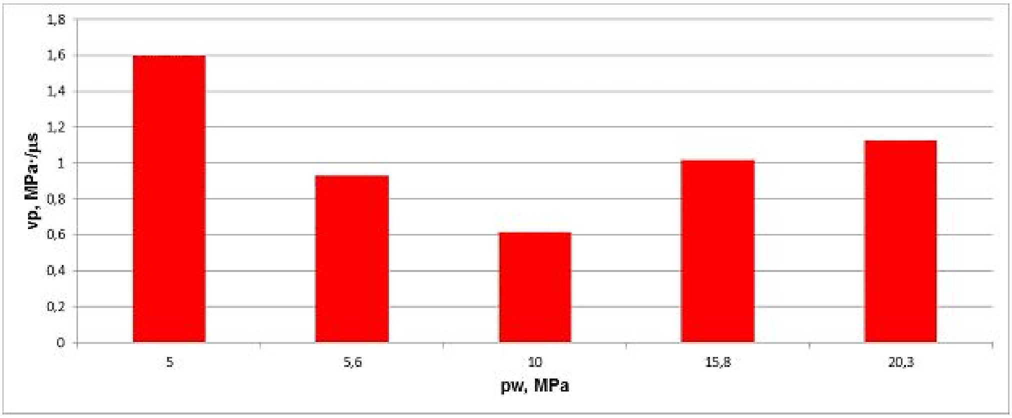

Fig. 9. Pressure increase rates during the explosion of a 10 g charge of EMULINIT PM for different confining pressures

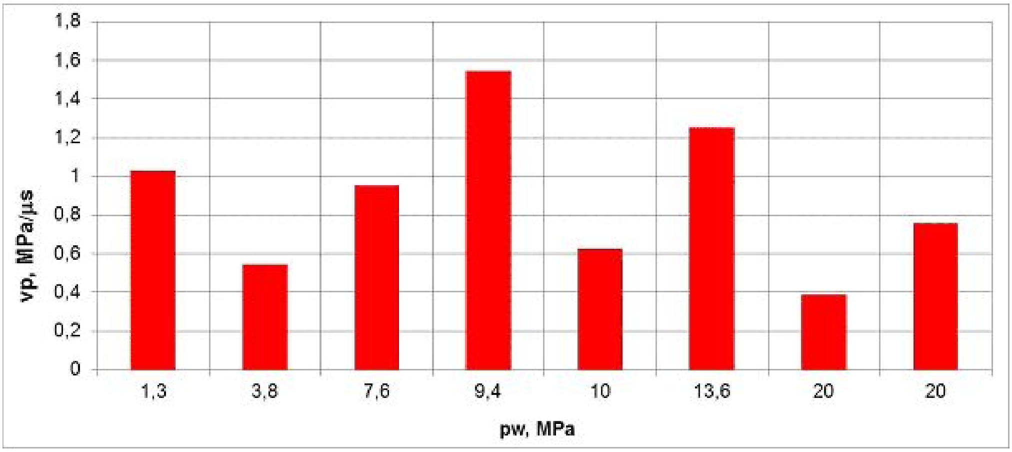

Fig. 10. Pressure increase rates during the explosion of a 10 g charge of METANIT SPECJAL E7H for different confining pressures

with a detonator and its hermetic inaccessibility enabled pressure to be maintained at a desired level until the explosion. Previous studies were conducted with a maximum confining (initial) pressure of 20 MPa, and the scope of these works covered two types of explosives – EMULINIT PM and METANIT SPECJAL E7H produced by Nitroerg S.A. Both materials and detonators maintained their ability to explode well above the pressure declared by the manufacturer.

The analysis of the obtained results leads to the conclusion that both tested materials maintain their ability to explode with increased confining pressure. The amount of energy produced during the explosion oscillates at a fixed range for both of the explosives when the same amount of charge is used. The value of energy production increases slightly with confining pressure.

The obtained results of the initial studies are promising and these studies will be continued in the nearest future. This work opens up new areas of research on blasting agents (combustible materials, propellants and explosives) for the development and design of new types of charge, which will ultimately increase the efficiency of explosive charges in a borehole and improve the efficacy of methods used in rock burst and methane prevention.

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