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Cast composite explosives based on hexogen with the maximum detonation parameters

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Plastic-bonded explosives (PBX) with a high content of explosive components (80-85%) are obtained by varying the hexogen granulometric composition and the optimization of polyurethane binder composition based on polyether polyol. Hexogen with bimodal, trimodal and continual particle size distributions is used. The best characteristics of production and full reproducibility of PBX quality are achieved by using the trimodal RDX. Physical, chemical and mechanical characteristics, shock sensitivity and detonation parameters for the Chapman-Jouguet (CJ) condition are determined. The maximum values of detonation parameters are achieved with the composition of 84% hexogen and 16% polyurethane binder (D=8120 m/s, P=220 kbar). These results are compared with the measured detonation velocity and the pressure results of composite explosives based on octogen and PBX theoretical detonation parameters.

Key words: **Composite explosives, polyurethane elastomer, hexogen, detonation parameters, explosive characteristics.**

Introduction

THE alternatives to conventional melt-cast TNT-based compositions are polymer-bonded explosives (PBX), made by incorporating crystals of high explosives materials (hexogen RDX, octogen HMX, oksynitrotriazole ONTA…) in a polymerizable liquid binder matrix. Immediately after the preparation, they are directly loaded into equivalent ammunition by the casting technology and, by programmed crosslinking at elevated temperaturs, they turn into a solid explosive charge with rubber-elastic characteristics.

In relation to TNT-based explosives, PBX are more convenient for processing, manipulation, transport and storing, less susceptible to cracking and dimensional unstability under the thermal cycle, less sensitive to exploitation condition changes (they have lower sensitivity to energetic pulses), and they have better mechanical characteristics. PBX application can easily satisfies high energetic performance and low sensitivity, two opposite demands for a high-quality explosive charge.

A mass content of the explosive component and the load density have the dominant effect on PBX detonation parameters. The maximum detonation velocity, the detonation pressure and other values of detonation wave parameters can be achieved with an explosive charge of high density and a crystalline explosive content higher than 80 mass.%. The PBX processing with high crystalline explosive content needs to solve two basic problems, because of present technological problems. The first one is the determination of the optimum particle size distribution of the explosive component that would enable the lowest composite mixture viscosity, high degree of physical-chemical homogeneity (small porosity) and thus high final PBX density. The second problem is the optimization of the factors that dictate the polymeric binder viscosity (the ratio of functional groups, the plasticizer, catalyst and bonding agent content, etc.) and the degree of loading the polymer with the explosive component. Rheological behavior of highly filled liquid polymers, such as uncured PBX, is the most important property determining the ease of processability and castability of composites.

The RDX-based PBX with a nonenergetic polyurethane binder are analyzed. The research results concerning the possibility of getting PBX with maximum detonation parameters, optimum RDX granulometric composition finding and a composite explosive with high RDX mass content characterization are presented. The experimental detonation velocity and the pressure values are compared with the measurement results of the detonation parameters of HMX-based composite explosives and the theoretical calculation results of the PBX detonation parameters obtained by the EXPLO5 program [1].

Experimental results and discussion

PBX processing

The PBX processing is realized by using an optimized composition of a nonenergetic polymer binder, multimodal mixture of RDX crystals, modern equipment (Planetron HKV vertical mixer) and full control of technological parameters and the remote control of processing [2,3]. The polyurethane elastomer is synthesized by polycondensation of toluene diisocyanate (TDI–80) and liquid polyether poliol (by the "one shot" method). Different additives are added into the elastomer to adjust its physical properties, such as catalyst (ferric acetylacetonate), bonding agent (triethylene-tetramine) and antioxidant (fenil-β-naphthylamine). A plasticizer (dioctyladipate) and a wetting agent (lecithin) are used to ensure processing characteristics that

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facilitate mixing and casting of the uncured PBX compositions.

The bimodal, continual and trimodal RDX granulometric mixtures were used as explosive components for PBX preparing. Hexogen was of seven types:

- the recrystalized hexogen RDX-I, RDX-II and RDX-III with the bimodal particle size distribution and the granulation break in the large range,
- the recrystalized hexogen RDX-IV with the bimodal particle size distribution and the granulation break in the narrow range,
- the recrystalized (PR-RDX) and stabilized (ST-RDX) hexogen mixture with the continual particle size distribution, RDX-V and RDX-VI,
- the recrystalized hexogen RDX-VII with the trimodal particle size distribution.

The granulometric composition of hexogen is determined by the sub sieve analysis. Figs.1-3 show the particle size distribution and the cumulative curves of three types of the used heksogen: RDX-V, RDX-VI and RDX-VII. The main difference among the given three is that the granulation RDX-VII contains a larger proportion of fine particles.

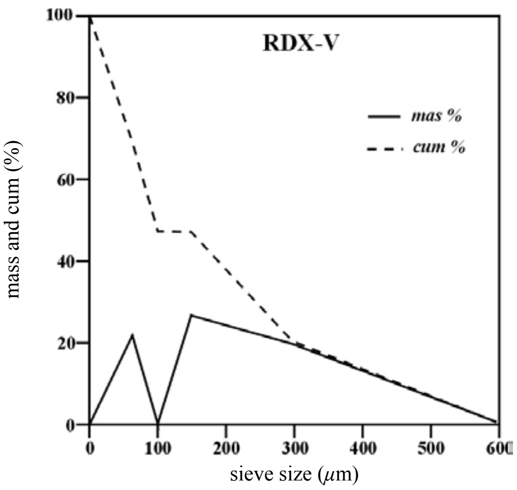

Figure 1. The particle size distribution and the cumulative curve for RDX-V

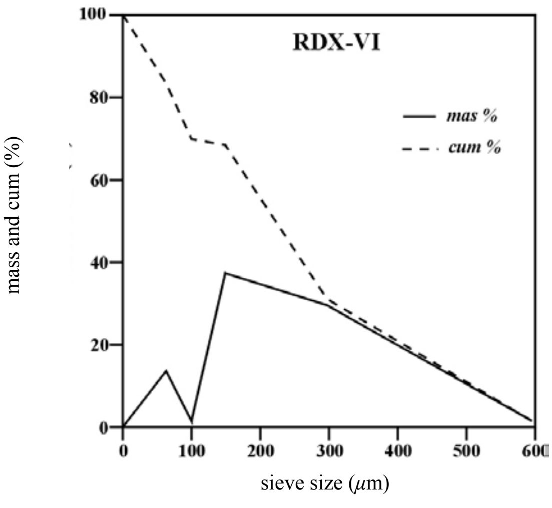

Figure 2. The particle size distribution and the cumulative curve for RDX-VI.

A bulk density was determined for every RDX granulation and a packing coefficient was calculated according to [4]. These values are presented in Table 1.

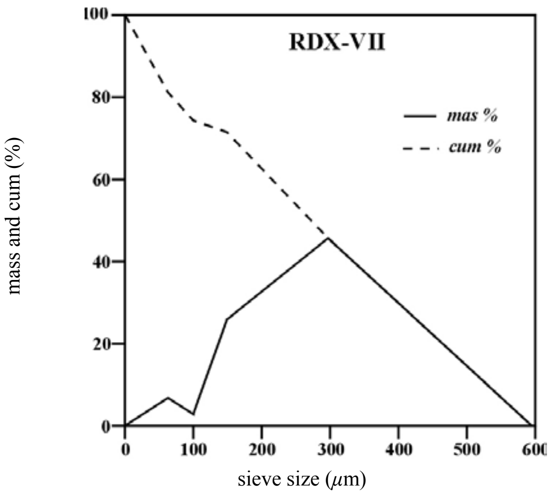

Figure 3. The particle size distribution and the cumulative curve for RDX-VII

Table 1. RDX granulations used for PBX processing

RDX granulations	RDX particle size and ratio sizes	Bulk density (g/dm^3)	Coeff. pack. p (%)
RDX-I	500-600μm:100-200μm=2.33:1	1150	63.18
RDX-II	400-500μm:100-200μm=2.33:1	1080	59.34
RDX-III	400-500μm:50-100μm=2.33:1	1065	58.52
RDX-IV	100-200μm:1-100μm=2.33:1	870	47.80
RDX-V	PR-RDX:ST-RDX =1:2	940	50.00
RDX-VI	PR-RDX:ST-RDX =2:1	1045	57.42
RDX-VII	200-500μm:150-300μm:1-100μm=2.5:1:1	995	54.67

A few explosive compositions (PBX-1 to PBX-14) were casted by using the RDX with determined granulations (Table 1). The RDX content varied from 80 to 85 mass. %; the necessity for these compositions to remain in pourable state during filling imposes limitations on the maximum viscosity of the uncured PBX and the amount of solids wich can be successfully incorporated into such compositions. An initial composition and its basic characteristics (density, porosity and detonation velocity) in the function of the particle size distribution and the RDX content are presented in Table 2.

Table 2. Cast PBX composition and characteristics

Explosive	PBX composition (mas.%)		RDX granulation	ρ (g/cm^3)	ν (%)	D (m/s)
	RDX	PB				
PBX-1	80	20	RDX-I	1.579	0.19	8020
PBX-2	80	20	RDX-II	1.542	2.55	7800
PBX-3	80	20	RDX-II	1.520	3.92	7700
PBX-4	82	18	RDX-IV	1.569	2.12	7910
PBX-5	80	20	RDX-V	1.568	0.89	7810
PBX-6	82	18	RDX-V	1.555	2.99	7630
PBX-7	80	20	RDX-VI	1.555	1.71	7860
PBX-8	81	19	RDX-VI	1.537	3.52	7750
PBX-9	82	18	RDX-VI	1.568	2.56	7870
PBX-10	80	20	RDX-VII	1.569	0.82	7870
PBX-11	82	18	RDX-VII	1.572	1.93	7910
PBX-12	83	17	RDX-VII	1.588	1.61	8020
PBX-13	84	16	RDX-VII	1.595	1.85	8120
PBX-14	85	15	RDX-VII	1.575	3.73	7970

The detonation velocity was measured in the steady-state detonation zone, in charges of 30 mm in diameter, by using an electric counter (method SNO 1475). The charges were boostered by FH-5 (ρ0 = 1.60 g/cm3).

A positive RDX-VII granulation influence on uncured PBX viscosity is illustrated in Fig.4. The composition viscosity was measured by the Brookfield viscometer HBT at a shear rate of 5 min-1. The measurement was carried out at a temperature of 30°C every 15 min. from the moment of adding TDI-80.

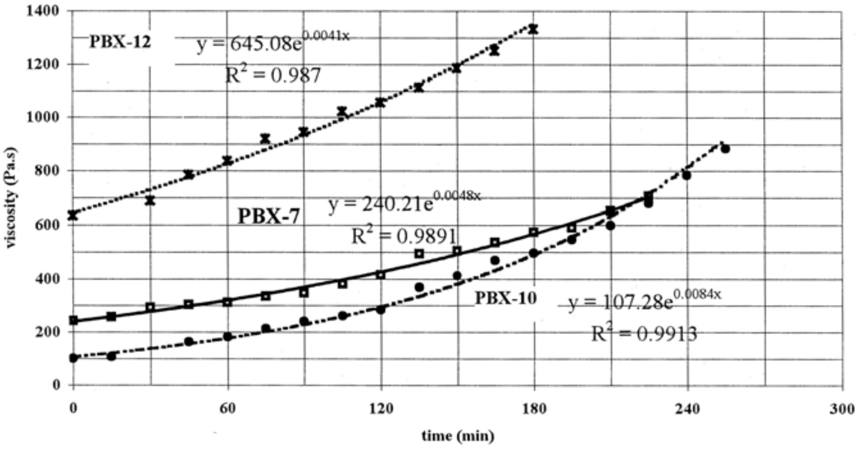

Figure 4. Viscosity for uncured PBX with a various content and granulation of RDX

It can be concluded that the high-density and the high-velocity PBX processing (Table 2, Fig.4) reaches a compromise between two contradictory demands – a high crystalline explosive content and satisfactory composite mixture rheological properties.

The corresponding RDX content capability is the function of uncured PBX viscosity, i.e. crystalline RDX granulation. The RDX with the bimodal particle size distribution: RDX-I, RDX-II and RDX-III, in spite of the packing theory assumptions, provide the most inviolable PBX processing characteristics. The high density and detonation velocity values for PBX-1 with 80 % RDX-I lead to a conclusion that the RDX-I granulation, with the highest packing coefficient, would be very convenient for the PBX processing by the extruding technology. The high viscosity of PBX-1 composite does not allow for the casting (mixing is difficult) of compositions that contain more than 80 % of solids.

The granulations of RDX-IV, RDX-V and RDX-VI enable an effective casting of compositions with 80–82% RDX, but not corresponding "building" of the RDX amount necessary for the maximum detonation parameters. The PBX-4 (with 82 % RDX-IV) and PBX-9 (with 82 % RDX-VI) compositions have almost the same densities, although the RDX bulk densities differ – the PBX charge quality cannot be predicted on the basis of the crystalline explosive bulk density value, as in case of hexolites and octolites [5,6].

The optimum properties and the highest degree of reproducibility of PBX compositions were obtained with the trimodal particle size distribution of hexogen RDX-VII. The following effects were achieved:

- both the initial viscosity (its value η = 100 Pas) and the rate of its increase with curing time for the uncured PBX-10, based on RDX-VII are lower than for the composition based on RDX-VI,
- the density of the PBX with 80 % RDX-VII is higher,
- the increase of the RDX content from 80% to 83% causes a significant increase in the initial viscosity of the uncured PBX-12, but it does not achieve the critical value for casting,
- the polymeric binder packing degree is higher with crystalline explosive, so the compositions with 84 % and 85 % RDX (PBX-13 and PBX-14) are obtained.

The high viscosity of PBX-14 does not allow for the casting of PBX compositions which contain more than 85 mass.% of solids.

PBX detonation parameters

The detonation pressure was determined for the compositions with a high RDX content (83-85 mass. %). A method with a low-resistance manganin pressure gage [7] was used. This parameter was measured in the steady-state detonation, by using the plane wave generator as a booster. An experimental sample, with an embedded gage, is shown in Fig.5. The detonation pressure values were taken from the *P*(*t*) profile bend point (CJ point), as illustrated in Fig.6-8. The results are presented in Table 3. The table includes the HMX-based PBX detonation parameter values, and the theoretical calculations given by using the EXPLO5 program, as well. The calculation was carried out for the PBX experimental density values by using the BKW (Becker – Kistiakovsky – Wilson) equation of state. The particle velocity results obtained by using the electromagnetic method with the pulse magnetic field [8] are also presented in Table 3.

The detonation parameters experimental values are the average values based on five experiments. The relative errors of the measurement methods are between 1 and 2 %.

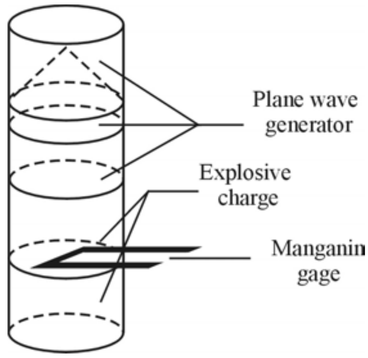

Figure 5. An experimental sample

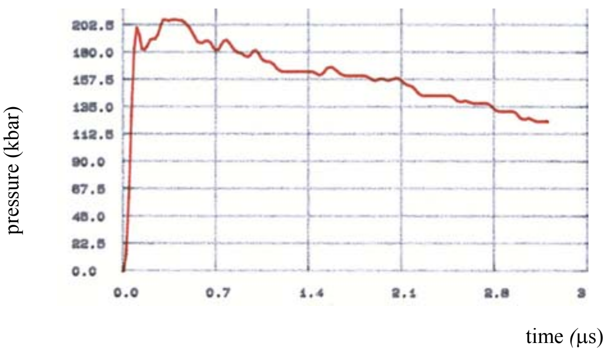

Figure 6. The *P*(*t*) profile for PBX-12

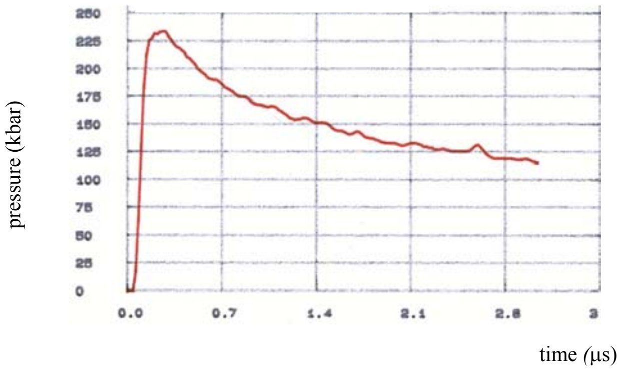

Figure 7. The $P(t)$ profile for PBX-13

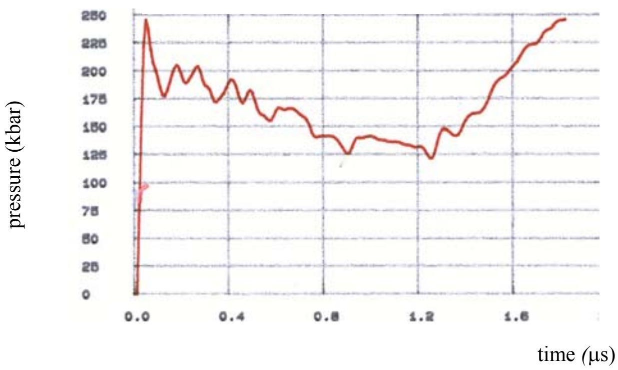

Figure 8. The $P(t)$ profile for PBX-14

Table 3. RDX- and the HMX-based PBX detonation parameters

Explosive	Detonation parameter	Experimental value	Calculated value	Explosive	Detonation parameter	Experimental value	Calculated value
PBX-7 (80% RDX) ρ=1.569	D	7870	7817.02	PBX (80% HMX) ρ=1.607	D	8250	7945.10
	P_{CJ}	196.3/216.4*	233.72		P_{CJ}	260/250*	247.77
	Q_V	-	-5558.42		Q_V	-	-5514.02
	μ_{CJ}	1746.6	1918.01		μ_{CJ}	1960	1948.77
	ρ_{CJ}	2.01	2.078		ρ_{CJ}	2.10	2.12
	n	3.51	3.08		n	3.20	3.07
PBX-12 (83% RDX) ρ=1.588	D	8020	7910	PBX (82% HMX) ρ_e=1.59	D	8150	7909.30
	P_{CJ}	210/219.4*	245.20		P_{CJ}	240/232*	245.12
	Q_V	-	-5671.89		Q_V	-	-5585.90
	μ_{CJ}	1722.7	1951.33		μ_{CJ}	1776.9	1949.21
	ρ_{CJ}	2.02	2.108		ρ_{CJ}	2.08	2.11
	n	3.65	3.05		n	3.63	3.06
PBX-13 (84%RDX) ρ=1.595	D	8120	7963.25	PBX (84% HMX) ρ=1.62	D	8220	8042.12
	P_{CJ}	220	248.87		P_{CJ}	-	254.59
	Q_V	-	-5710.38		Q_V	-	-5662.51
	μ_{CJ}	-	1953.25		μ_{CJ}	-	1954.16
	ρ_{CJ}	-	2.12		ρ_{CJ}	-	2.14
	n	-	3.08		n	-	3.11
PBX-14 (85%RDX) ρ=1.575	D	7970	7863.64	**Note**:ρ-explosive density (g/cm^3); D-detonation velocity (m/s); P_{CJ}-detonation pressure (kbar); Q_V-detonation heat (kJ/kg); u_{CJ}-detonation products velosity (m/s); ρ_{CJ}- detonation products density (g/cm^3); n-polytropic exponent (1). *-experimental results obtained by using the eletromagnetic method.			
	P_{CJ}	202	241.74				
	Q_V	-	-5743.52				
	μ_{CJ}	-	1951.83				
	ρ_{CJ}	-	2.095				
	n	-	3.03				

It can be concluded that the maximum relevant parameters for an explosive charge quality grade were obtained for the PBX-13 composition (with 84 % wt RDX), based on the measurement results, Table 3. The high density, detonation velocity and detonation pressure values and small porosity, υ = 1.85 %, point to very good explosive charge quality. The conclusions based on the HMX-based PBX results [9] and their theoretical calculations, are the same.

A satisfactory accordance of the detonation velocity values ($D_e > D_T$ for 1–2 %) and the deviation of the calculated pressure value from its experimental value ($P_e < P_T$ for 10–25 %) could be noticed for the experimental and calculated values for the RDX-based PBX detonation parameters, Table 3. Thus, this composite explosive detonation mechanism is more complex, so an ideal equilibrium detonation model cannot explain it.

The PBX-13 (with 84 mass. % RDX) detonation parameter values are approximately the same as the values for the PBX with 82 % wt HMX.

PBX shock sensitivity

Since the optimum of the characteristics was obtained in the composition PBX-13 with 84% RDX-VII, its more complete characterization was done by the examination of shock sensitivity.

The GAP Test was used to determine the critical shock pressure at which 50 % of the experiments result in a detonation. The PBX-13 shock sensitivity determination was carried out by using the following system: the booster, FH-5, (ϕ = 30 mm, ρ_0 = 1.60 g/cm^3) – the polyamide attenuator (ϕ = 32 mm) – the tested explosive charge (ϕ = H = 30 mm) – Al cylinder.

The critical shock pressure value was calculated from the following expression [10]:

$$P_{cr} = 203.32 \text{ x } e^{-72.824 \text{ x } l} \quad (1)$$

where ℓ is the polyamide thickness (mm). These results are presented in Table 4 and were compared with the hexolite, octolite and cast TNT values [10,11].

Table 4. PBX and TNT-based explosive charges shock sensitivity results

Type of explosives	ρ (g/cm^3)	ℓ (mm)	P_{cr} (bar)
PBX-13	1.595	22.8	39.1
Comp. B (hexolite)	1.70	32.40	19.55
Octolite 70/30	1.77	30.11	23.06
Octolite 80/20	1.82	32.07	20.02
Cast TNT	1.59	11.50	88.54

The PBX shock sensitivity (although it has a high mass content of an explosive component) is lower than the value for hexolite and octolite which is convenient for less vulnerable ammunition.

Conclusion

The research and presented results point to the following conclusions:

The rheological behavior of PBX systems is the most important characteristic that determines their processing capability during the casting process. In order to attain the maximum detonation parameters and to exhibit good properties, such compositions require a high content of the crystalline explosive, which can be achieved only by the use of a well adapted RDX grain size distribution.

The recrystalized hexogen with the bimodal particle size distribution and the granulation break in the large range (the packing coefficient is the highest) is more convenient for the PBX laboration by the extruding technology.

Very high quality of reproducibility is obtained from batch to batch of the PBX compositions with RDX-VII, with the trimodal particle size distribution and ~ 23 mass.% of fine fraction (↓100 μm) content. For that granulation of RDX, and the polyurethane binder systems, the maximum solid loadings achievable from the cast technology is 85 mass.%.

The analysis of the experimental density, detonation velocity and pressure values points to the fact that the relevant parameters maximum is found in the PBX with 84 % wt RDX-VII (ρ_0 = 1.59 g/cm^3, ν = 1.85 %, D=8120 m/s, P_{CJ} = =220 kbar). The detonation parameters are almost the same as the values obtained for the PBX with 82 mass.% HMX.

The low detonation velocity and pressure values for the composition with 85 % wt RDX are the consequence of the nonuniform density distribution in the explosive charge and high porosity (ν = 3.73 %).

The composition with 84 mass.% RDX has lower shock sensitivity than the hexolite and octolite charges and it is the most convenient for less vulnerable ammunition.

The great deviation of the theoretical values of the detonation pressure from the experimental ones leads to the conclusion that the ideal detonation model (which is a basis for the EXPLO5 program) cannot successfully describe the detonation regime of the examined explosives, although the RDX-based PBX detonation velocity values are in good agreement.

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Liveni kompozitni eksplozivi na bazi heksogena maksimalnih parametara detonacije

Variranjem granulometrijskog sastava heksogena i optimizacijom sastava poliuretanskog veziva na bazi poliola, dobijeni su liveni kompozitni eksplozivi (PBX) sa visokim sadržajem eksplozivne komponente (80-85 mas.%). Korišćen je heksogen sa kontinualnom, bimodalnom i tromodalnom raspodelom veličina čestica. Najbolje proizvodne karakteristike i potpuna repoduktivnost kvaliteta PBX postižu se primenom heksogena sa tromodalnom raspodelom. Određene su fizičko-hemijske karakteristike PBX, osetljivost na inicijaciju udarnim talasom i parametri detonacije za uslove Chapman-Jouguet (CJ). Maksimalne vrednosti detonacionih parametara ostvarene su kod kompozitnog sastava sa 84 mas.% RDX i 16 mas.% poliuretanskog veziva (D= 8120 m/s, P= 220 kbar). Rezultati su upoređeni s eksperimentalnim vrednostima brzine i pritiska detonacije PBX na bazi oktogena, kao i sa rezultatima teoretskog proračuna detonacionih parametara.

Ključne reči: **kompozitni eksplozivi, poliuretanski elastomer, heksogen, parametri detonacije, eksplozivne karakteristike.**

Explosifs composites coulés à base d'hexogène avec les paramètres de détonation maximaux

Les explosifs à liant plastique (PBX) à teneur élevée en composantes explosives (80-85%) sont obtenus par changement de la composition granulométrique d'hexogène et par optimisation de la composition du liant polyurèthane à base de polyéther polyol. On a utilisé l'hexogène dont la distribution des dimensions de particules était bimodale, trimodale et continue. Les meilleures caractéristiques de la production et la reproductibilité complète de la qualité de PBX sont obtenues par le RDX trimodale. Les propriétés physiques, chimiques et mécaniques sont déterminées aussi bien que la sensibilité au choc et les paramètres de détonation pour les conditions de Chapman – Jouguet. Les valeurs maximales de paramètres de détonation sont obtenues avec la composition qui comprend 84% d'hexogène et 16% de liant polyurèthane (D=8120 m/s, P=220 kbar). Ces résultats sont comparés à la vélocité de détonation mesurée et aux résultats de la pression d'explosifs composites basés sur les paramètres de détonation théorétiques d'octogène et de PBX.

Mots-clés: **explosifs composites, élastomère polyuréthane, hexogène, paramètres de détonation, propriétés explosives.**