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Influence of Content and Dispersion of Octogene and Oxidizer on the Mechanical Properties of Cast Aluminized PBX

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The effect of the content and dispersion of the explosive and oxidation components on the mechanical behavior of polyurethane binder based composite explosives (PBX) was investigated. Experiments were planned by using local simplex planning of the third order, under which 13 compounds were cast, with planned variation of three factors. Thirteen octogene and five ammonium perchlorate granulations, with different amount of coarse and fine fraction, were used for PBX manufacture. PBX mechanical characteristics under uniaxial tension, at 20ºC, 50ºC and -40ºC, were determined. Mathematical models, which adequately describe dependences of PBX mechanical characteristics on the level of variations of analysed factors, were obtained.

Key words: **explosives, cast explosives, octogene, polyurethane binder, ammonium perchlorate, mechanical characteristics.**

Abbreviations and symbols

PBX – Polimer bonded explosives
HMX – Octogen
Al – Aluminium
AP – Ammonium perchlorate
σ_m – Tensile strength
ε_m – Strain at maximum load
ε_p – Strain at rupture
E – Modulus of elasticity
t_R – Value of Student t-test

Introduction

CAST composite explosives based on a polymer as a binder (PBX) represent "filled" polymers, i.e. three component systems which consists of a rigid filler, a borderline layer with changed polymer characteristics and a polymer the characteristics of which are similar to "unfilled" polymers (Fig.1). The properties of PBX compounds, especially rheological and physico-mechanical, are not only determined by the phase and physical condition of the polymeric matrix, nature of their chains and elastomeric network elements , but also by the influence of the rigid filler on the structure and characteristics of the borderline polymer , as well as –filler particles interactions [1-2].

High fill in level and adequate filler particles dispersion result in particle agregation and binding of adsorption surrounding polymer layers, which in turn builds direct interaction of all PBX compound ingredients. If the matrix perfectly sticks to the filler surface, the characterictics of the "filled" polyurethane elastomers depend on the structure and the interaction of soft, flexible segments and urethane groups in the polimer chain as well as the curing density. Free rotation and configuration ability of soft segments provide composite compound elasticity, flexibility and ability of reverse deformation (effect of "self-curing"). Rigid segments represent physical curing of elastomers which are mutually connected in the domain by the means of hydrogen connections. Their volume increase results in an increase of rupture stress and modulus of elasticity, and a decrease in compound stretching power.

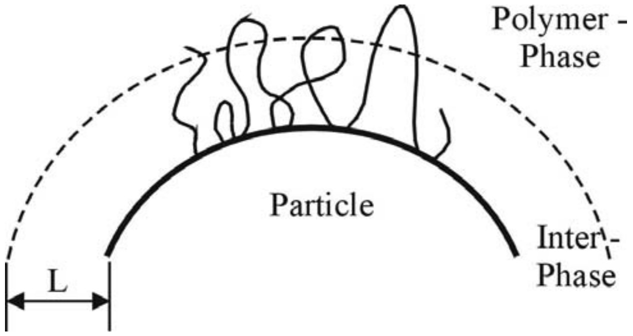

Figure 1. Illustration of the area close to the particle filler [1].

The viscoelastic behavior and mechanical characteristics of those energetic materials are not only determined by structural elastomer characteristics but also by the interaction of the matrix with the filler surface and the filler-filler interaction. The borderline layer between the polymer phase and the filler surface or the interphase plays a very important role during mechanical extortion which is common for all composite materials. This interphase includes polymer molecules the motions of which are influenced by their proximity to the filler surface. Within this interphase, the molecular motions of individual molecules are changed due to weak mutual attachments or attachments to neighbouring particles. The

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density of polimeric chains in this region is considered to be greater than that of the bulk polymer phase due to attracting forces near the surface [1]. "Loops" which spreads from contiguious points with particles to the main section, i.e. the bulk polymer phase, are presented in Fig.1. The median loops distance from the surface (labelled with L) represents interphase thickness.

Many explanations of filled polymers characteristics are based on the existence of this intermediate layer. To provide a satisfactory adhesion between the particle filler and elastomers, it is necessary to optimize the additive content in the binder which will minimize laceration of their linkage during corresponding tension. Since the dispersion of metallic, corrosive and explosive components plays an important role for extension characteristics, the total amount of a large fraction in a composite compound also represents an optimization parameter of the PBX mechanical behaviour.

Description and understanding of PBX mechanical properties is essential for utilizing response-reaction of laborated ammunition on mechanical tensions especially those which can generate unwanted initiation of these energetic materials. In addition, precisely determined parameters of the explosive tension state can serve as a production quality measurement, since they are closely connected with the polymer morphology which develops during manufacturing process. The critical tension level which a polymer can endure is one of criteria for the mechanical durability of explosives.

Discovery of micromechanical phenomena, especially polymer separation from the filler surface (dewetting) is extremely important not only for defining the parameters of the PBX mechanical status during storage, transportation and exploitation, but also for improving sensitivity, reliability and life cycle estimate of these materials. New developments indicate that the mechanical stability of filling of explosives is the characteristic which limits exploitation time of combat resources, in other words it is most critical for system functioning.

The study explores the effect of the content and the dispersion of octogen (HMX) and ammoniumperchlorate (AP) on the mechanical characteristics of the aluminized PBX. Based on the applied experimental plan for obtained responses, the derived mathematical models which adequately describe dependability of tensile strength, extension and modulus of elasticity of the PBX content in a defined fluctuation area that affects the HMX and AP amount and dispersion. To assess the quality of PBX reproductiveness, density values of cast compositions are defined.

Illustration and analysis of experimental results

PBXs are manufactured according to [3-4]. Compounds with a constant content of the solid phase (80 mas.%) are analysed.

The following components are used:

- Bimodal mixture of coarse (150-500μm) and fine (50-150μm) octogene, HMX-K/HMX-S,
- Aluminium powder with a mean diameter size of 15μm,
- Bimodal mixture of coarse (200μm) and fine (~ 10μm) ammonium perchlorate, AP-K/AP-S and
- Polyurethane binder based on polyether polyol [5].

Drafting the planned matrix of the local simplex experimental plan

The experiment was performed according to the method of local simplex - lattice planning of the partial third series, under which thirteen compounds were cast, with a planned area of HMX and AP granulation fluctuation. Solid phase consisted of 15 mas.% coarse fraction AP-K, 25 mas.% aluminum, as well as art of 40 mas.% within which the variation of the following factors are planned:

- x_1 fine granulation ammonium perchlorate, AP-S
- x_2 fine granulation octogene, HMX-S
- x_3 coarse granulation octogene, HMX-K.

When a level of factor variation was chosen, care was taken to get required and rheologically acceptable PBX compounds.

The experimental plan provides the calculation of regression coefficients of partial cubic model polynoms.

In a real coordinate system the chosen experimental area is linked to the simplex-lattice plan domain by encoded values of coordinates.

$$x_1 = 0,5\,X_1 + 0,1\,X_2 + 0,1\,X_3 \tag{1}$$

$$x_2 = 0,1\,X_1 + 0,5\,X_2 + 0,1\,X_3 \tag{2}$$

$$x_3 = 0,4\,X_1 + 0,4\,X_2 + 0,8\,X_3 \tag{3}$$

where:

x_1, x_2, x_3- real coordinates in the working matrix,

X_1, X_2, X_3- coordinates of the plan matrix.

Selected levels of factor variations are illustrated in the working matrix for local simplex of the third series for real coordinates and in the plan matrix for encoded coordinates (Table 1 and 2).

Table 1. Working matrix with real values

WORKING MATRIX				
granulation	label	Y_1	Y_2	Y_3
AP-S	x_1	50	10	10
HMX-S	x_2	10	50	10
HMX-K	x_3	40	40	80

Table 2. Matrix plan with encoded values

MATRIX PLAN				
granulation	label	Y_1	Y_2	Y_3
AP-S	X_1	1	0	0
HMX-S	X_2	0	1	0
HMX-K	X_3	0	0	1

The total experimental areas for the three-component system, as well as the area of the discussed plan with experimental points are presented in Figures 2 and 3 respectively. Some of the experimental points served as the control points, where the verification of the model adequacy is performed using statistical analysis methods.

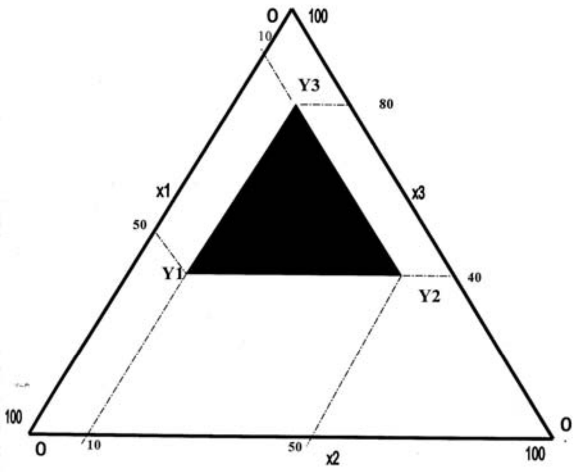

Figure 2. Plan location in the working matrix

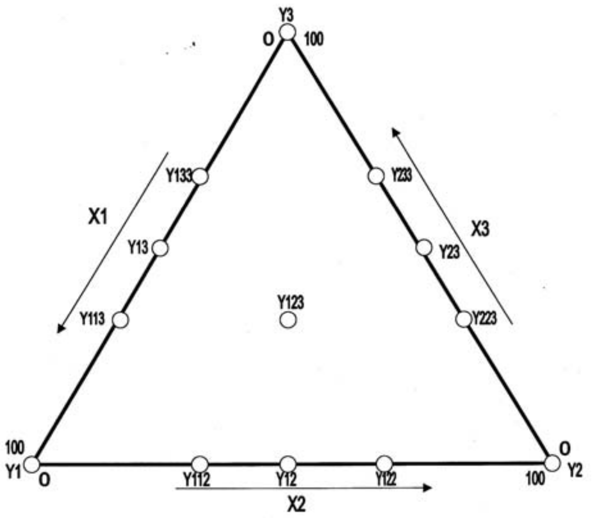

Figure 3. Matrix domain with experimental points

According to the experimental plan there were developed 13 HMX granulations and 5 AP granulations (mixing coarse and fine fraction in an adequate mass ratio) which were used during PBX composition (Tables 3 and 4).

The matrix of the simplex-lattice plan with the fraction quantities of HMX and AP bimodal mixture for 13 formulations done according to the experiment plan are shown in Table 5.

The investigated responses are: tensile strength (σ_m), strain at maximum load and at rupture (ε_m i ε_p), as well as elasticity module (E) na 25ºC, 50ºC and - 40ºC.

Table 3. Octogene granulations used for PBX production

HMX labels	mas.% HMK-K	mas.% HMX-S
HMX-1	80,00	20,00
HMX-2	44,44	55,56
HMX-3	88,89	11,11
HMX-4	69,57	30,43
HMX-5	63,16	36,84
HMX-6	84,21	15,79
HMX-7	52,17	47,83
HMX-8	86,96	13,04
HMX-9	59,26	40,74
HMX-10	74,07	25,93
HMX-11	57,14	42,86
HMX-12	85,71	14,29
HMX-13	66,67	33,33

Table 4. Oxidizers granulations used for PBX production

AP labels	mas.% AP-K	mas.% AP-S
AP-1	42,86	57,14
AP-2	78,95	21,05
AP-3	61,64	38,36
AP-4	50,56	49,44
AP-5	55,56	44,44

Density is also measured (calculated as porosity from the relation between experimental and theoretical density values), but only as a parameter for reproductiveness value.

Table 5. Fraction ratios of HMX and AP according to the experimental plan

No. of exper.	abel of ex-per.	working matrix			mas. %			total HMX, mas.%	AP-S in mixture, mas.%	HMX-S in mixture, mas.%
		x_1	x_2	x_3	x_1	x_2	x_3			
1	Y1	50	10	40	20,00	4,00	16,00	20,00	57,14	20,00
2	Y2	10	50	40	4,00	20,00	16,00	36,00	21,05	55,56
3	Y3	10	10	80	4,00	4,00	32,00	36,00	21,05	11,11
4	Y123	23,33	23,33	53,33	9,33	9,33	21,33	30,67	38,36	30,43
5	Y112*	36,67	23,33	40	14,67	9,33	16,00	25,33	49,44	36,84
6	Y113*	36,67	10	53,33	14,67	4,00	21,33	25,33	49,44	15,79
7	Y122*	23,33	36,67	40	9,33	14,67	16,00	30,67	38,36	47,83
8	Y133*	23,33	10	66,67	9,33	4,00	26,67	30,67	38,36	13,04
9	Y223*	10	36,67	53,33	4,00	14,67	21,33	36,00	21,05	40,74
10	Y233*	10	23,33	66,67	4,00	9,33	26,67	36,00	21,05	25,93
11	Y12	30	30	40	12,00	12,00	16,00	28,00	44,44	42,86
12	Y13	30	10	60	12,00	4,00	24,00	28,00	44,44	14,29
13	Y23	10	30	60	4,00	12,00	24,00	36,00	21,05	33,33
NOTE: *control points										

The dependence of the PBX mechanical characteristics as a function of variable factors is defined by a common mathematical model of partial third order:

$$Y = b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + \\ + b_{23}X_2X_3 + b_{123}X_1X_2X_3 \qquad (4)$$

where:

Y	response values
b_1, b_2, b_3	regression coefficients for the partial cubic model,
b_{12}, b_{13}, b_{23}	regression coefficients of double interactions,
b_{123}	regression coefficients of triple interactions,
$X_{1,2,3}$	encoded coordinates in the experimental area for the local simplex.

Regression coefficient values (evaluation of their values) are calculated from experimental response values according to [6]. Adequacy testing is performed for every response using the Student t-test:

$$t_R = \frac{\Delta y\,\sqrt{n}}{S_y\sqrt{1+\xi}} \qquad (5)$$

where:

Δy	absolute difference value between the calculated and the experimental (measured) test value,
n	repeated test values,
S_y	average test deviation for the observed response
ξ	coefficient (depending on the point position in simplex plan and mixture composition).

On the basis of the attained values at the control points of the simplex plan (label with “*” in table 5), the value of Student t-test t_R was evaluated and compared with the table t-test value t_T for the chosen reliability (α) and the calculated degree freedom.

If the calculated t-criterion is lower than the table value, the mathematical model equation then describes the response in an adequate manner.

Dependence of the PBX mechanical characteristics on the content and the dispersion of octogene and ammonium perchlorate

Examinations of the PBX mechanical characteristics were carried out on the universal tester “INSTRON”, by uniaxial tensile testing of specimens, and the crosshead speed of 50 mm/min. The results of the examinations (the mean values of seven single measurements) and standard deviations (S_y), are given in Table 6. The PBX porosity values, calculated on the basis the density measurements, are given in Table, too.

The results are arranged by means of statistical analysis and the obtained regression equations describe the dependency of examined values in the function of the analysed factors. Across the coded coordinates of the experimental area, the graphic review represents the values of tensile strength, strain at maximum load and at rupture and the PBX modulus of elasticity.

Table 6. Results of PBX mechanical characteristics measurement

T [ºC]	20				50				-40			
Test number/porosity PBX (%)	σ_m [MPa]	ε_m [%]	ε_p [%]	*E* MPa]	σ_m [MPa]	ε_m [%]	ε_p [%]	*E* [MPa]	σ_m [MPa]	ε_m [%]	ε_p [%]	*E* [MPa]
1/4,71	0,585	15,85	22,96	5,57	0,513	14,21	16,87	8,34	12,17	1,47	1,94	491,22
2/3,14	0,527	15,18	21,93	5,41	0,419	11,16	14,74	6,28	9,66	2,17	2,78	256,28
3/7,25	0,386	18,60	34,72	3,00	0,291	15,80	25,91	3,45	7,29	2,99	3,98	248,49
4/3,08	0,700	14,41	19,31	6,24	0,443	13,32	17,91	9,28	8,15	4.14	4,91	163,66
5/4,96	0,576	13,80	29,04	6,30	0,571	13,58	17,19	7,46	12,67	1,82	2,39	307,16
6/4,73	0,478	17,36	27,51	4,55	0,408	18,53	26,28	4,60	11,96	1,62	2,02	417,53
7/4,39	0,628	14,00	20,59	6,49	0,481	10,60	14,70	9,60	9,80	2,08	2,82	247,40
8/5,48	0,572	13,57	29,35	5,63	0,456	10,70	17,09	7,52	7,39	4,74	5,51	224,50
9/5,88	0,390	13,42	35,15	4,73	0,433	11,06	18,24	7,62	8,16	2,05	3,22	369,01
10/9,88	0,438	15,67	27,87	5,14	0,350	12,51	17,12	4,30	8,12	1,72	2,45	354,84
11/3,59	0,713	14,23	20,67	7,45	0,463	13,55	16,79	7,35	8,32	3,73	5,05	153,02
12/4,56	0,475	18,03	36,35	4,58	0,386	12,98	19,55	4,93	10,18	2,70	3,24	184,89
13/4,87	0,502	13,29	31,89	5,20	0,468	11,30	17,19	8,88	9,17	1,78	2,37	269,28

PBX tensile strength

Eqs 6-8, as mathematical models describing tensile strength change (σ_m) at three test temperatures, as in Tables 7-9, are illustratively given for the adequacy verification results, according to eq.5.

$$Y_\sigma^{50} = 0,513\,X_1 + 0,419\,X_2 + 0,291X_3 \text{ - } 0,012X_1X_2 \text{ -} \\ -0,064X_1X_3 + 0,452X_2X_3 \text{ - } 0,174X_1X_2X_3 \tag{6}$$

$$Y_\sigma^{20} = 0,585X_1 + \ 0,527X_2 + 0,386X_3 + 0,628X_1X_2 - \\ -0,042X_1X_3 + 0,182X_2X_3 + 3,114X_1X_2X_3 \tag{7}$$

$$Y_\sigma^{-40} = 12,17X_1 + 9,656X_2 + 7,292X_3 \text{ - } 10,376X_1X_2 + \\ +1,792X_1X_3 + 2,768X_2X_3 \text{ - } 24,645X_1X_2X_3. \tag{8}$$

The graphic review of tensile strength values, gained over coded values is given in Figures 4 and 5.

Table 7. Adequacy verification of the tensile strength model at 50°C

control points	*y*	*Y'*	t_{izr}	*A* (t_{cal}<t_{tab})
*Y*112	0,571	0,479	1,64	ADEQUATE
*Y*113	0,408	0,425	0,30	ADEQUATE
*Y*122	0,481	0,448	0,59	ADEQUATE
*Y*133	0,456	0,351	1,87	ADEQUATE
*Y*223	0,433	0,477	0,78	ADEQUATE
*Y*233	0,350	0,434	1,50	ADEQUATE
Sy = 0,0584 MPa *f* = 7 α= 0,05 t_{tab} = 2,36				

Table 8: Adequacy verification of the tensile strength model at 20°C

control points	*y*	*Y'*	t_{izr}	*A* (t_{cal}<t_{tab})
*Y*112	0,576	0,705	2,25	ADEQUATE
*Y*113	0,478	0,509	0,55	ADEQUATE
*Y*122	0,628	0,686	1,01	ADEQUATE
*Y*133	0,572	0,443	2,25	ADEQUATE
*Y*223	0,390	0,520	2,27	ADEQUATE
*Y*233	0,438	0,473	0,62	ADEQUATE
Sy = 0,0596 MPa *F* = 7 α= 0,05 t_{tab} = 2,36				

Table 9. Adequacy verification of the tensile strength model at -40°C

control points	*y*	*Y'*	tizr	*A* (t_{cal}<t_{tab})
*Y*112	12,674	9,026	31,07	NONADEQUATE
*Y*113	11,960	10,942	8,67	NONADEQUATE
*Y*122	9,805	8,188	13,77	NONADEQUATE
*Y*133	7,392	9,316	16,39	NONADEQUATE
*Y*223	8,156	9,483	11,30	NONADEQUATE
*Y*233	8,116	8,695	4,93	NONADEQUATE
Sy = 0,122 MPa *f* = 7 α= 0,05 t_{tab} = 2,36				

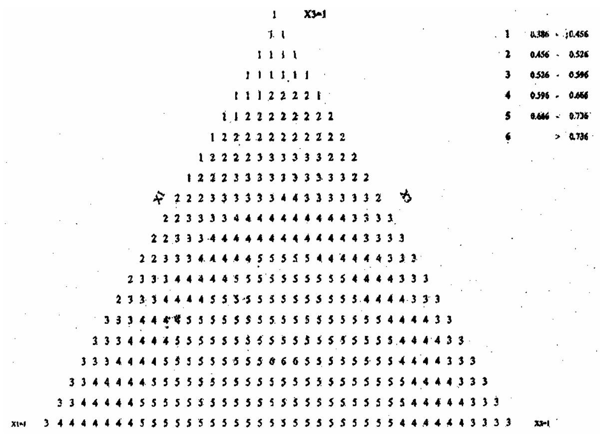

Figure 4. Values of the tensile strength at 20°C

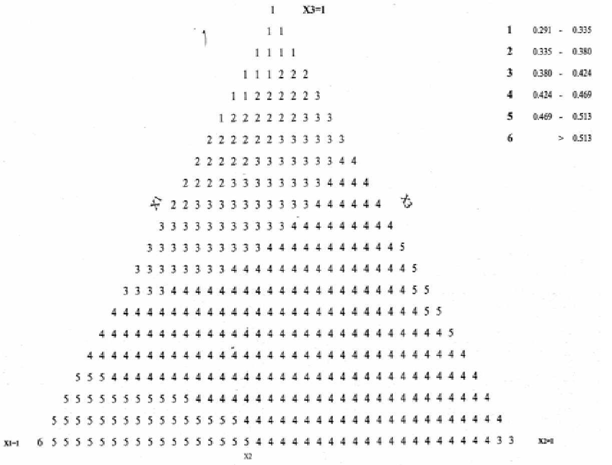

Figure 5. Values of the tensile strength at 50°C

The results have shown that the attained models can describe the tensile strengths at 50°C and 20°C in the adequate manner, but for the results at -40°C a large dispersion value of adequacy have been obtained, so the regression equation (8) does not describe in adequate manner the dependence of σ_m on the content and the dispersity of HMX and AP.

The contents of fine fractions of octogen and ammonium perchlorate (factors X_1 and X_2) have the largest influence on tensile strength value. The higher levels of these factors show the positive effect on the measured response. The reproductivity assessment of PBX quality can be done on the basis the uniaxial tensile results. It is evident that the lowest tensile strengths are obtained using the significant porosity compositions, including the coarse and fine fractions AP and HMX at the same time. The octogen content effect has not been evinced (in the examination limit range from 20 mas.% to 36 mas.%) if the fine fractions quotient of AP and HMX in the composite mixture are appropriate (test 1 and 2).

Increasing the temperature leads to a moderate reduction of PBX tensile strength, but a significant change of tensile strength occurs by decreasing the temperature. The rise of σ_m at extreme temperatures (at 50°C - 22%, and at -40°C - 26%), can be achieved by increasing the fine fraction content of AP, which means that AP-S in the total HMX/AP mixture gives the composite compositions more stable to temperature change.

On the basis of the graphic illustrations of tensile strength values (Figures 4 and 5), response levels for certain verification levels can be estimated. The limit values of σ_m are from 0.386 MPa to 0.736 MPa – three temperatures total changing amount 75%- 90%. The maximum tensile strength values are moved from ~ 50 mas.% of the HMX-K content (point Y_{123} of the experimental plan, test 4), to compositions close to the point Y_1 (test 1) –to the increasing content of AP-S in the mixture, by rising the temperature.

Strain at PBX maximum load

The mathematical model that describes the change of strain at maximum load at three test temperatures is represented by equations 9-11:

$$\begin{aligned} Y_{\varepsilon m}^{50} &= 14{,}21X_1 + 11{,}16X_2 + 15{,}8X_3 + 3{,}46X_1X_2 - \\ &-8{,}1X_1X_3 - 8{,}72X_2X_3 + 29{,}19X_1X_2X_3 \end{aligned} \tag{9}$$

$$\begin{aligned} Y_{\varepsilon m}^{20} &= 15{,}85\,X_1 + 15{,}18\,X_2 + 18{,}6\,X_3 - 5{,}14\,X_1X_2 + \\ &+3{,}22\,X_1X_3 - 14{,}4\,X_2X_3 - 8{,}64\,X_1X_2X_3. \end{aligned} \tag{10}$$

$$\begin{aligned} Y_{\varepsilon m}^{-40} &= 1{,}47\,X_1 + 2{,}17\,X_2 + 2{,}99\,X_3 + 7{,}64\,X_1X_2 + \\ &+1{,}88\,X_1X_3 - 3{,}2\,X_2X_3 + 33{,}150\,X_1X_2X_3. \end{aligned} \tag{11}$$

The verification of their adequacy across equation 5 has shown that the strains at the maximum load at three temperatures can be successfully described by mathematical models ($t_{cal} < t_{tab}$).

The graphic illustrations of the ε_m values are shown in Figures 6 -8.

The analysis of the diagrams confirms the inverse ratio between X_1 and X_2 factor level verifications and the examination response – strain is dropped increasing the AP-S and HMX-S contents, but raised if the content of HMX-K is increased. The limit values of ε_m at 20°C are 13.2% - 18.60%. The stretching power of composite mixtures are retained by increasing the temperature, thereby the response maximum is moved to larger amounts of AP fine fractions, else content remission of both fractions of octogen.

A significant degradation of the PBX stretching power is noticed at -40°C. It is, probably, in relation with test temperature which is very near to glass point of using polyurethane elastomer (T_g = -53°C [7]). Very small strains (1.47% - 4.74%) indicate that tested compositions are almost near or in the glass phase at that test temperature.

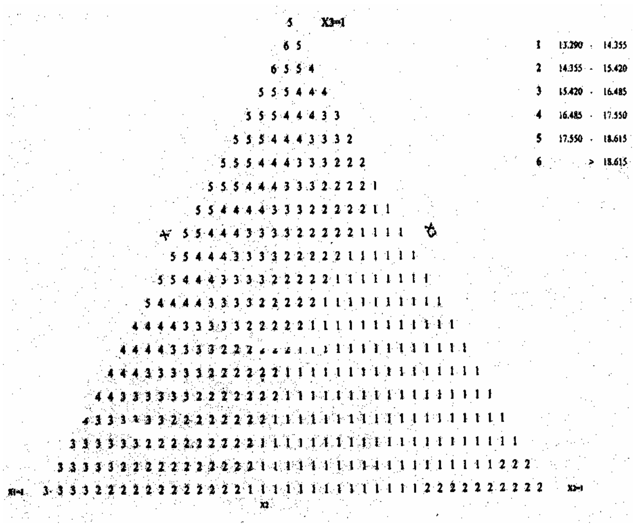

Figure 6. Graphic illustration of ε_m at 20°C

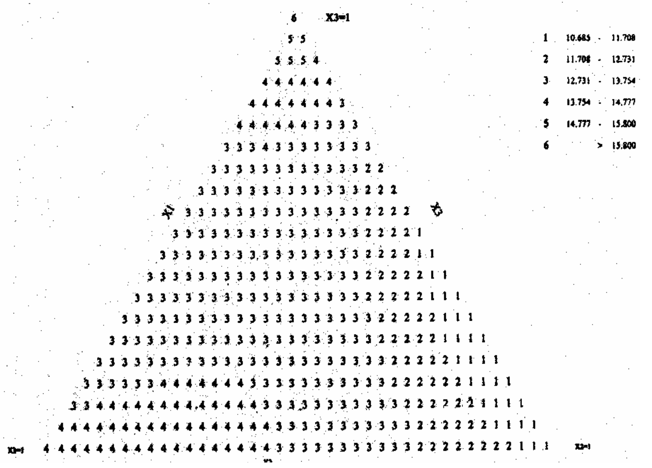

Figure 7. Graphic illustration of ε_m na 50°C

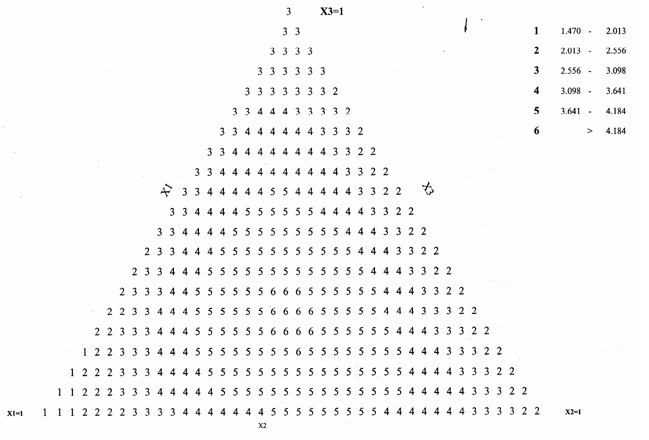

Figure 8. Graphic illustration of ε_m at -40°C

It is a great change of response in the examination experimental area. In the temperature interval from 20°C to 50°C the same one is not too significant (40% - 50%), while the aperture of the obtained responses at -40°C is more considerable and amounts to 185%. The smallest strain values are the most represented ones in the experimental area, about 50%. By lowering the temperature, the maximum strain values are gained for the composition in the center of the experimental area, around the Y_{123} point of the plan, test 4, Table 5.

Strain at rupture of PBX

The results of adequacy verification of the obtained mathematical models, presented by equations 12-14, have shown that the same models describe the changes of strain at rupture in the same adequate manner at all three test temperatures.

$$Y_{\varepsilon_r}^{50} = 16,87X_1 + 14,74X_2 + 25,91X_3 + 3,94X_1X_2 - \\ -7,36X_1X_3 - 12,54X_2X_3 + 13,77X_1X_2X_3. \quad (12)$$

$$Y_{\varepsilon_r}^{20} = 22,96\,X_1 + 21,93\,X_2 + 34,72\,X_3 7,1\,X_1X_2 + \\ +30,04\,X_1X_3 + 14,26\,X_2X_3 - 306,72\,X_1X_2X_3. \quad (13)$$

$$Y_{\varepsilon_r}^{-40} = 1,941\,X_1 + 2,78\,X_2 + 3,976\,X_3 + 10,758\,X_1X_2 + \\ +1,126\,X_1X_3 - 4,032\,X_2X_3 + 30,791\,X_1X_2X_3 \quad (14)$$

The obtained strains, via coded values, are given in Figures 9-11.

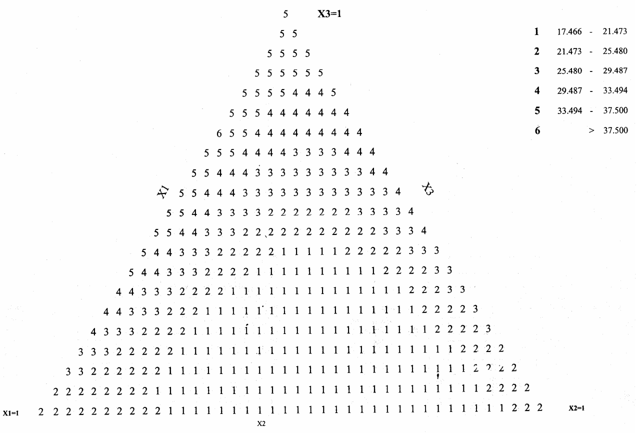

Figure 9. Graphic illustration of the strain at rupture at 20°C

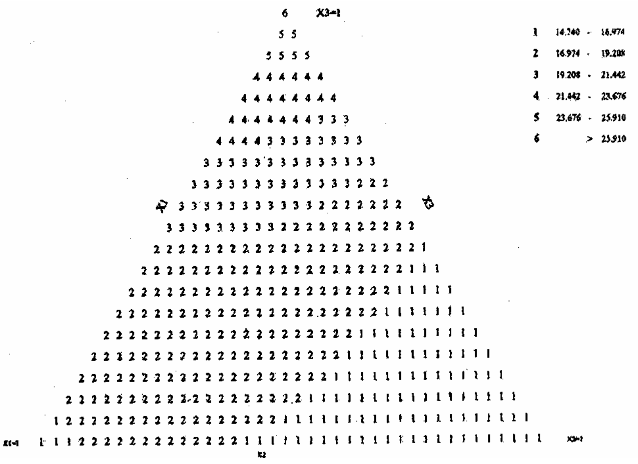

Figure 10. Graphic illustration of the strain at rupture at 50°C

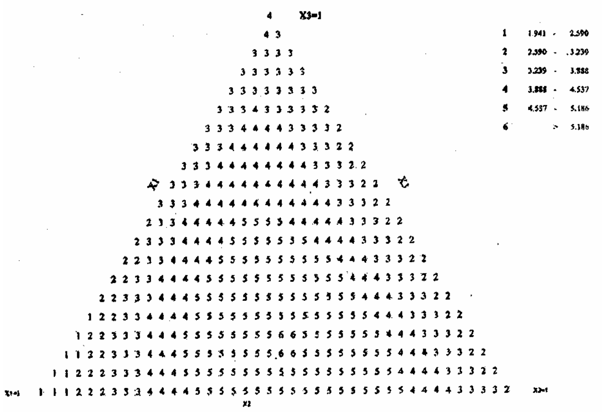

Figure 11. Graphic illustration of the strain at rupture at -40°C

The strain at rupture of PBX is determined by variation levels of X_1 and X_3 factors to a great extent. The highest values are gained for large porosity compositions with embedded coarse fractions of AP and HMX. Great differences between ε_p and ε_m are noticed at these PBX mixtures which indicate adsorption, i.e. the polymer-filler bond accidence. Owing to the parting of phases at the contact area ("dewetting"), the tensile properties of polymer binder are determined by mechanical beahavior of these compositions. It is necessary to optimize the "bonding" agent content in PBX or to use more convenient bimodal mixture combinations of octogen and oxidator diminishing the distinctions. The mixtures: AP-1 and HMX-1, AP-2 and HMX-2, such as AP-3 and HMX-4 enhance significantly the deformation and as in [8], contribute to upgrading the output characteristics of PBX.

The limit values of the strain at rupture at 20°C are from 17.5% to 37.5%. Increasing the temperature brings about their moderate drop, while at -40°C the rapid reduction is evident.

For any desirable value in the strain at rupture changing area, as seen in Figures 9-11, a lot of different compositions can be selected. The change of ε_p in the whole temperature range is from 75% to 165%. Increasing the temperature, the maximum values are moved to minimum contents of AP-S, i.e. to the maximum contents of HMX-K. It is significant that the smallest values occupied about 50% of the obtained mathematical model graphic review at 20°C and 50°C. It means that changing the PBX composition procures a considerably sharper progress trend of that mechanical value approaching to point 3 of the experimental area, when the HMX-K content (factor X_3) rises and the AP-S and HMX-S contents diminish. It is noticed that strain at rupture values show a progressive growth by increasing the variation level of the factor X_3, i.e. when the HMX-K tromodal mixture content is above 70%.

Modulus of elasticity of PBX

Equations 15-17 represent the mathematical models describing the modulus of elasticity change at three test temperatures. The statistical analysis of the obtained responses shows that the adequate models are obtained at 20°C and 50°C, but at –40°C a large dispersion of values of adequacy has been presented.

$$Y_E^{50} = 8,34\,X_1 + 6,283\,X_2 + 3,451\,X_3 + 0,15\,X_1X_2 - \\ -3,878\,X_1X_3 + 16,056\,X_2X_3 + 50,883\,X1X_2X_3 \quad (15)$$

$$Y_E^{20} = 5,567\,X_1 + 5,407\,X_2 + 3,0\,X_3 + 7,868\,X_1X_2 + \\ +1,17\,X_1X_3 + 3,97\,X_2X_3 + 3,663\,X1X2X3. \tag{16}$$

$$Y_E^{-40} = 491,12\,X_1 + 256,2\,X_2 + 248,49\,X_3 - 882,7\,X_1X_2 - \\ -739,65X_1X_3 + 67,6\,X_2X_3 + 120,13\,X_1X_2X_3. \tag{17}$$

The values of PBX elasticity modulus at 20°C are preceded from 3.00 MPa to 7.45 MPa. The fine fraction oxidator content (factor X_1) has the greatest effect on the modulus value. The mixtures upgrading the larger quantity of both fine fractions of AP and HMX show the highest response values.

Increasing the temperature does not produce significant modulus changing at a great number of considered compositions. At 50°C, the severe response rise is noticed at mixtures with a larger content of filler coarse fractions only, i.e. with non adequate granulations of HMX and AP. The noticeable differences signify that the exposure of these compositions to elevated temperatures induces the afterward curing. The limit values of *E* are from 153.02 MPa to 491.22 MPa. The value change in the test temperature range is 150-200% (Figures 12 and 13).

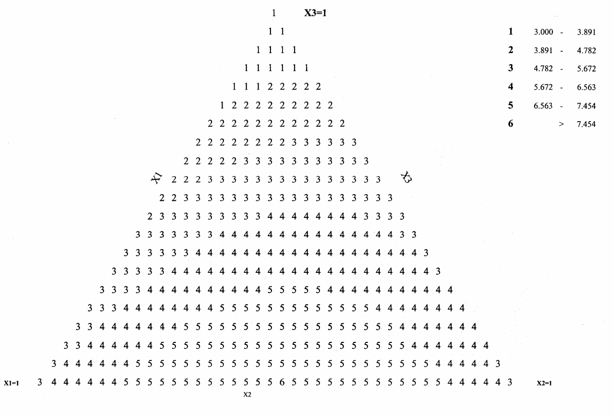

Figure 12. Graphic illustration of E at 20°C

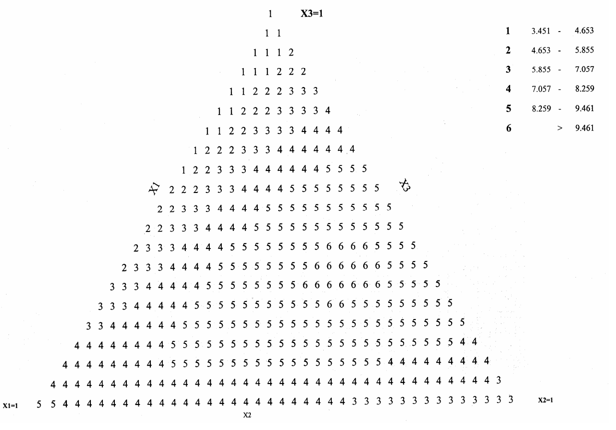

Figure 13. Graphic illustration of E at 50°C

By recapitulating the mechanical characteristic test results (Table 6) it can be noticed that the stretching power of the analysed compositions failed significantly by decreasing the temperature, besides the amplification of tensile strength, and particularly the modulus of elasticity at the same time. These results are in accordance with the examination results of the PBX compositions presented in [9-11]. It is shown that mechanical measurement deviations of these composite explosive types are most considerable at low temperatures, close to the glass temperature of the filled polymer.

The obtained mathematical models, such as graphic illustrations, enable insight to the analysed response character change and the most favourable combination choice of factor variation levels for concrete established requirements for mechanical characteristics of PBX.

Conclusion

The effect of the content and the dispersion of the explosive and oxidation components on the mechanical behavior of cast (PBX) based on octogen, ammonium perchlorate, aluminium and polyurethane elastomer was investigated. According to the local simplex lattice plan of the third order, thirteen PBX compositions were prepared including the planned variation area of fine AP and HMX fractions (factors X_1 and X_2) and octogen (factor X_3) coarse fraction contents.

The mechanical characteristics of PBX at 20ºC, 50ºC and -40ºC as responses are determined. The analysed results of uniaxial tension and the graphic review of the response areas showed that the dependence of PBX tensile strength and modulus of elasticity at 20°C and 50°C, such as strains at maximum load and at rupture at all three test temperatures, can be described in an adequate manner using mathematical models. Adequacy verification of the mathematical models is performed at the control points of the experimental matrix plan, on the basis of the Student's *t*-test values.

Depending on the variation level of quantity and coarse and fine fractions of HMX and AP ratio, the following limit values of the measuring responses at 20 °C are attained: σ_m=0.386-0.713 MPa; ε_m=13.29-18.60%; ε_p=19.31-36.35% and *E*=3.00-7.45 MPa. The mechanical characteristic change is rather small by increasing the temperature, while decreasing the temperature causes rapid fall of the stretching power, simultaneously including the rise of tensile strength value and particularly the modulus of elasticity of PBX.

The tensile strength and the elasticity modulus of PBX are predominantly affected by the content of small HMX and AP fractions. Increase of these contents result in the rise of σ_m and E values, at different HMX/AP ratio levels.

The X_3 factor has the most intensive effect on the stretching power of PBX. The strains ε_m and ε_p are inversely proportionate to the fine fraction content of explosive and oxidation components, but is directly related to the coarse HMX fraction content. There are recorded great differences between ε_p and ε_m at high porosity mixtures, which means that the bonding agent content and the total quantity of coarse fractions in „filled" polymer are the optimization parameters of PBX mechanical behavior. It is obvious that the smallest strain values are the most represented ones in the experimental area, about 50%.

Octogen and ammonium perchlorate composite mixture contents do not affect the mechanical characteristics of PBX to a great extent in relation to the effect of their dispersions.

A considerable range of mechanical characteristics in a function of HMX and AP dispersion in the simplex area has been found. The change of the tensile strength and the modulus of elasticity values is (75-90)% and (150-200)%, respectively, at all three test temperatures. The strain at maximum load is changed about (40-50)% at 20ºC and 50ºC and the strain at rupture - (75-165)% in the whole temperature range. The possibility to measure amplification values in such a wide range by means of an adequate combination choice of explosive and oxidation component dispersion is of great significance, in order to make an adequate combination of analysed factors as well as to prepare PBX with defined mechanical behavior parameters in advance. It is also possible to make a quick selection of mixtures which are not desirable in accordance with the examined characteristics.

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Uticaj sadržaja i disperzije oktogena i oksidansa na mehaničke osobine livenih aluminiziranih PBX

Ispitan je uticaj sadržaja i disperzije eksplozivne i oksidacione komponente na mehaničko ponašanje livenih kompozitnih eksploziva na bazi oktogena i poliuretanskog veziva (PBX). Pri planiranju eksperimenta primenjen je lokalno simpleks-rešetkasti plan trećeg reda, prema kojem je izliveno trinaest sastava sa planiranim područjem variranja tri faktora. Za izradu PBX korišćeno je trinaest granulacija oktogena i pet granulacija amonijumperhlorata, sa različitim učešćem krupne i sitne frakcije. Kao dozivi, određene su mehaničke karakteristike pri jednoosnom istezanju, na 25°C, 50°C i -40°C. Dobijeni su matematički modeli koji adekvatno opisuju zavisnosti zatezne čvrstoće, izduženja pri maksimalnoj i prekidnoj sili i modula elastičnosti kompozitnih sastava, u funkciji nivoa variranja analiziranih faktora.

Ključne reči: **eksplozivi, liveni eksplozivi, oktogen, poliuretansko vezivo, amonijumperhlorat, mehaničke karakteristike.**

Влияние содержания и дисперссии октогена и окислителя на механические свойства литых алюминиевых PBX

В настоящей работе испытано влияние содержания и дисперссии взрывчатого и окислительного компонентов на механическое поведение литых композитных взрывчатых веществ на базисе октогена и полиуретанового вяжущего вещества (PBX). При планировке эксперимента применён местный симплекс - решётчатый план третьей степени, по которой вылито тринадцать составав с планированной зоной вариаций трёх факторов. Для выработки PBX использовано тринадцать гранулей октогена и пять гранулей аммония перхлората, с различным участием крупной и мелкой фракции. В роли отклика определены механические характеристики при одноосном вытягивании на 25°C, 50°C и -40°C. Получены матеметические модели, адекватно описывающие зависимость затяжной прочности, вытягивания при максимальной и прерывной силой, а в том числе и модуля упругости композитных структур, в функции уровня вариаций анализированных факторов.

Ключевые слова: взрывчатые вещества, литые взрывчатые вещества, октоген, полиуретановое вяжущее вещество, аммоний перхлорат, механические характеристики.

Influence du contenu et la dispersion d'octogène et d'oxydateur sur les propriétés mécaniques des PBX de fonte

L'effet du contenu et la dispersion de la composante explosive oxydante sur le comportement mécanique des explosifs de fonte composés à la base d'octogène et du liant polyuréthane (PBX) a été étudié. En préparant le projet de cet essai on a appliqué le plan simplex local du troisième ordre d'après lequel on a fondu treize composés avec la région projetée des variations de trois facteurs. Pour fabriquer les PBX on a utilisé treize granulations d'octogène et cinq granulations d'ammonium perchlorate avec la différente participation de grosse et fine fraction. Comme réponse on a déterminé les caractéristiques mécaniques pendant l'extension uniaxe à 25ºC, 50ºC et -40ºC. Les modèles mathématiques qui décrivent, de façon adéquate, les dépendances de la résistance à la tension, l'extension à la force maximale et le module d'élasticité des composés en fonction du niveau des variations des facteurs analysés ont été obtenus.

***Mots clés*: explosifs, explosifs de fonte, octogène, liant polyuréthane, ammonium perchlorate, caractéristiques mécaniques.**