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Enhancing the explosive characteristics of a Semtex explosive by involving admixtures of BCHMX and HMX

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ABSTRACT

A well-known ternary plastic explosive, Czech Semtex 1H, contains a mixture of PETN and RDX softened by SBR. In this work, BCHMX was used to replace PETN in Semtex 1H to form Sem-BC+RDX. In addition, another mixture based on BCHMX and HMX as energetic fillers bonded by the polymeric matrix of Semtex 1H (Sem-BC+HMX) was studied. The particle size distribution of each individual explosive was determined to obtain the optimum mixing conditions. Friction and impact sensitivities were determined. The velocity of detonation was reported practically and the detonation properties were calculated by EXPLO5 code. The explosive strength of each sample was measured by the ballistic mortar test. The conclusion confirms that the velocity of detonation of Sem-BC+HMX was the highest in comparison with the prepared samples. Sem-BC+RDX has the least impact and frictions sensitivities. Sem-BC+RDX has higher detonation velocity, detonation properties and explosive strength than Semtex 1H. Addition of BCHMX in Semtex 1H as a replacement for PETN is the candidate to produce a high performance advanced Czech plastic explosive.

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1. Introduction

Plastic explosives are produced by several companies and commercially available under different trade names. Mainly the composition of the plastic explosive contains energetic material bonded by desensitizing polymeric matrix [1,2]. The new trend in the field of plastic explosive is the addition of advanced inexpensive energetic materials to enlarge the performance [3–6]. Several publications presented the replacement of the traditional explosive such as 1,3,5-trinitro-1,3,5-triazinane (RDX) and pentaerythritol trtranitrate (PETN), used for production of commercial available plastic explosives, by advanced explosives such as 2,2-dinitroethylene-1,1-diamine (FOX-7), *cis-1*,3,4,6-tetranitrooctahydroimidazo-[4,5-*d*]imidazole (BCHMX), 1,3,5,7-tetranitro-1,3,5,7-tetrazocane (HMX) and 2,4,6,8,10,12-hexanitro-2,4,6,8,10,12-hexaazaisowurtzitane (CL-20) [7–10]. Decreasing the sensitivity and increasing the performance of the plastic explosives were obtained by using the advanced explosives [11–14]. In addition, the influence of the advanced explosives on the thermal stability of the studied plastic explosives was discussed [15–17]. Also the decomposition kinetics of advanced energetic materials mixed with different binder systems were also discussed by variable methods [18–21]. By comparing the performance characteristics, it was concluded that BCHMX has performance close to HMX and higher than RDX and PETN [3]. Sensitivity to impact of BCHMX is close to that of PETN while its thermal stability is better [22]. It means that BCHMX might be candidate to replace PETN in several applications. Interesting in this sense is ternary PBXs with the contents of BCHMX, in which it is possible by the suitable combination of the active fillers and binders to achieve optimal combination of performance and initiatory reactivity [23,24]. One of the well-known ternary PBXs, still from the period of Vietnam War, is Semtex 1H from the assortment of the Czech company Explosia. It is a high performance plastic explosive containing a mixture of RDX

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and PETN bonded by plasticized SBR rubber [25]. The presence of PETN in this PBX ensures its safe definite initiation by the detonator no.8. Semtex 1H has higher performance compared with the Semtex 1A [25] which contains butadiene-styrene rubber (SBR) up to 17 wt.% of the composition. This study discussed the possibility of replacing PETN by BCHMX for increasing the detonation characteristics of the traditional Semtex 1H by forming composition Sem-BC+RDX. In addition, another composition based on replacement of RDX by HMX to form new composition Sem-BC+HMX was studied. Other selected traditional plastic explosives produced by different countries such as Semtex 1A [7], Sprängdeg m/46 [9] and EPX-1 [26] were studied for comparison. The sensitivity to different mechanical stimuli, the velocity of detonation and the relative explosive strength were determined practically. While the properties of detonation were calculated by EXPLO5 code. Also several relationships based on the obtained results were presented and discussed.

2. Experimental

2.1. Fabrication of plastic explosives

2.1.1. Materials

PETN is a product of Explosia company while RDX is obtained from Dyno Nobel. HMX with particle size of class 3 was obtained from Russia [7]. BCHMX was prepared by two stage method according to patent [27] then a recrystallization process was performed to obtain the desired particle size. Polystyrene-butadiene rubber (SBR) and HM-46 oil (oil) were used for preparing the polymeric matrix. For comparison in this study, the Czech explosives Semtex 1A, containing PETN (83 wt.%) and SBR with oil (17 wt.%), and Semtex 1H (86% of the mixture PETN/RDX and 14% of the softened SBR binder), the Swedish military explosive Sprangdeg m/46 containing PETN (86 wt.%) and viscous oil (14 wt.%), and the Egyptian plastic explosive EPX-1 (86% PETN and 14% plasticized binder) were studied.

2.1.2. Determination of particle size

The particle sizes of all the individual explosives were determined using particle size distribution analyzer Partica LA-950 (produced by HORIBA). The measurement is based on the laser scattering method. The measurements based on determining the intensity in a correlation with the angle of light scattered from a particle, followed by the calculation of the particle size using Mie-scattering theory (Laser diffraction). Software was used to determine the size of the particles based on the light scattered. The curves of the particle distributions are plotted in Fig. 1.

From the curves of the particle sizes distributions, it was observed that BCHMX has mean particle size of 16 μm and the diameter of cumulative (90%) is 25 μm while the mean particle size of PETN is 14 μm and the diameter of cumulative (90%) is 20 μm. These results confirm that the crystal size of BCHMX is suitable for the replacement of PETN without affecting the mixing homogeneity with the polymeric matrix. On the other side, the mean particle size of RDX is 152 μm with diameter of cumulative (90%) is 282 μm while HMX has mean particle size of 201 μm and the diameter of cumulative (90%) is 426 μm. It means that HMX has wider range of particle size than RDX and this might affect the homogeneity and the sensitivity characteristics of the prepared plastic explosive.

2.1.3. Preparation of the plastic explosives

Semtex 1H is a plastic explosive produced by Explosia Company, Czech Republic. The polymeric matrix was prepared by the swelling of SBR using the oil in order to increase the elasticity of the binder. The production is based on direct mixing of 58 wt.% of RDX in addition to 28 wt.% of PETN with 14 wt.% polymeric matrix in a computerizing mixer plastograph BRABENDER. The composition was mixed for 30 min at 70 °C followed by 40 min mixing under vacuum at the same temperature. The product was extruded to form cylinders with diameter of 16 mm. Sem-BC+RDX was prepared by the same procedure using 58 wt.% of RDX and 28 wt.% of BCHMX. Also Sem-BC+HMX is based on 58 wt.% of HMX and 28 wt.% of PETN.

2.2. Elemental analysis

In order to determine the % of *C*, *H* and *N* in the produced explosive, PerkinElmer 2400 CHNS/O elemental analyzer was used. The obtained elemental analysis was recalculated to be referred to the N wt.% presented in the original particular explosive and presented in Table 1. This calculated summary formula was used as a representative of particular explosive and so it can be used as a formula in EXPLO5 code to calculate the detonation parameters of the explosives compositions.

2.3. Heat of combustion

Calorimeter model MS10A was used to determine the heat of combustion of the explosives compositions. The process based on the ignition of the composition in a bomb filled by excess of oxygen [28]. The obtained result was presented in Table 1. The heat of formation was calculated based on the measured heat of combustion, then it was used in the software for the detonation properties calculations.

2.4. Impact sensitivity measurements

An exchangeable drop hammer BAM impact test was applied to determine the impact energy required for initiation [29]. 50 mm^3 of each sample was tested using exchangable drop weights (2–5 kg). The probit method was applied to analyse and predict the initiation level probability [30]. The results recorded in Table 2 represent the impact energy with initiation probability of 50% successful trials of the tested samples.

2.5. Friction sensitivity measurements

The sensitivity to friction of the samples was measured by BAM friction test [29]. Each sample was spreaded on a rough porcelain plate where exchangable masses were added at different distances to vary the force between the pistil and the plate. Sound, smoke, or smell is characteristics of the sample initiation. Applying the Probit method [30], the friction force required for each sample with initiation probability of 50% successful trials was presented in Table 2.

2.6. Measurements of detonation velocities

The ionization copper probes connected with an oscilloscope (Tektronix TDS 3012) [29] was applied to record the velocities of detonation for the different compositions. Cylinders of explosive compositions have diameter of 1.6 cm and 20 cm length were formulated. The probes were placed inside the explosive cylinders at 5 cm distance from the booster and with 5 cm distance between each consequence probes. Semtex 1A was used as a booster and was initiated by electric detonator. Each sample was measured three times and the mean value of the measurements (with ±72 m/s as a maximum difference) was recorded in Table 2.

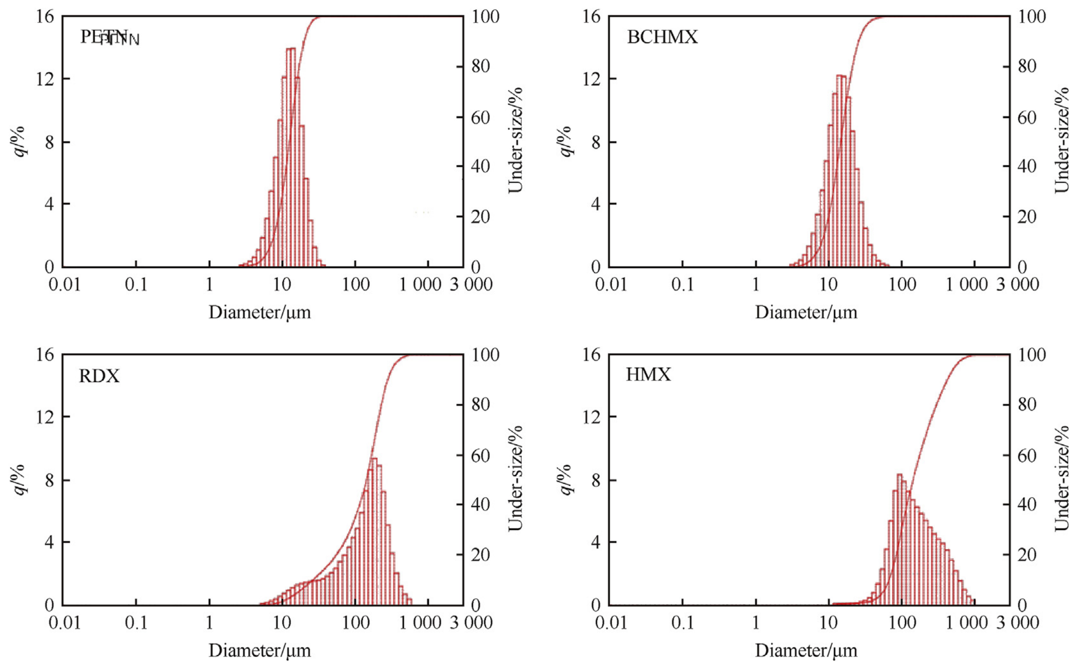

Fig. 1. Particle size distribution of the individual explosives.

Table 1
The information required for the detonation properties calculations.

No.	Explosive type	Formula	Mol. weight/(g mol^{-1})	Heat of combustion/(J g^{-1})	Heat of formation/(kJ mol^{-1})
1	Semtex 1H	$C_{6.39}H_{11.36}N_{5.34}O_{7.91}$	289.57	13736 ± 38	−175
2	Sem-BC+RDX	$C_{6.08}H_{10.57}N_{6.67}O_{6.61}$	282.88	14038 ± 45	74.7
3	Sem-BC+HMX	$C_{7.26}H_{12.35}N_{8}O_{7.95}$	338.92	14012 ± 53	115.9
4	Semtex 1A [7]	$C_{9.15}H_{14.85}N_{3.90}O_{11.42}$	362.22	14003	−660.2
5	Sprängdeg m/46 [7]	$C_{8.10}H_{12.81}N_{4}O_{10.90}$	340.63	13179	−539.2
6	EPX-1 [26]	$C_{7.88}H_{12.36}N_{4}O_{12.59}$	364.58	11528	−666.5
7	PETN [7]	$C_5H_8N_4O_{12}$	316.15	8182	−538.7
8	RDX [7]	$C_3 H_6 N_6 O_6$	222.14	9522	66.2
9	HMX [7]	$C_4 H_8 N_8 O_8$	296.18	9485	77.3
10	BCHMX [7]	$C_4H_6N_8O_8$	294.17	9124	236.5

Table 2
The measured characteristics of the studied explosives.

No.	Explosive type	Impact energy/J	Friction sensitivity/N	Density/(g cm^{-3})	Detonation velocity measured/(m s^{-1})	Explosive strength/(% TNT)
1	Semtex 1H	20.2	233	1.53	7568 ± 58	133.8 ± 02
2	Sem-BC+RDX	21.6	262	1.56	7721 ± 64	134.1 ± 0.3
3	Sem-BC+HMX	18.9	248	1.59	7852 ± 72	134.3 ± 0.3
4	Semtex 1A [9]	13.7	187	1.47	7318	128.5 ± 0.2
5	Sprängdeg-m/46 [9]	14.2	183	1.52	7520	131.8 ± 0.3
6	EPX-1 [26]	13.9	176	1.55	7636	133.9 ± 0.4
7	PETN [9]	2.9	44	1.70[a]	8400[a]	–
8	RDX [9]	5.6	120	1.80[a]	8750[a]	–
9	HMX [9]	6.4	95	1.90[a]	9100[a]	–
10	BCHMX [9]	3.2	88	1.79[b]	8650[b]	–

[a] Data obtained from Ref. [31].
[b] Data obtained from Ref. [32].

2.7. Relative explosive strength

The relative explosive strength of the compositions with respect to TNT explosive was determined using the ballistic mortar device [29]. A mass of 10 g sample was rotated inside a foil made of polypropylene and placed inside the mortar containing the projectile. Safety fuze was used to initiate the plain detonator. The pendulum swing angle represents the explosive strength of the sample and recalculated with respect to TNT [29]. Each sample was measured three times and the mean value of the measurements is presented in Table 2.

2.8. Calculation of the detonation characteristics

The calculated detonation parameters summarized by velocity of detonation, D, heat of detonation, Q, pressure of detonation, P) of the studied compositions were obtained using the EXPLO5 code [33]. The BKW equation of state was used based on the set of parameters of BKWN. The used parameters were: $\alpha = 0.5$, $\beta = 0.298$, $\kappa = 10.50$, $\Theta = 6620$. The detonation parameters were recorded in Table 3.

3. Results and discussion

As discussed in the experimental part, the particle size of the used explosives has a significant effect on the characteristics of the prepared plastic explosives. This effect might be clarified also by the sensitivity of the prepared samples. The studied sensitivities (impact and friction) are reported in Table 2 and a semi-logarithmic relationship between impact sensitivity and log friction sensitivity of the samples is plotted in Fig. 2.

Three groups were observed based on the sensitivities measurements. The first group connecting together the individual pure explosives as high sensitive materials to the mechanical stimuli (impact sensitivity less than 7 J and friction force less than 120 N). The second group includes the traditional plastic explosives based on PETN as explosive filler. The high sensitivity of PETN, which forms "individual group" affects the characteristics of its compositions where the impact sensitivities are in the range of 13.5–14.5 J. The third group includes the plastic explosives based on new compositions, Sem-BC+HMX and Sem-BC+RDX in addition to traditional plastic explosive, Semtex 1H. The sensitivity of Semtex 1H decreased due to mixing of PETN and RDX with the polymeric matrix. Sem-BC+RDX has the least sensitivities to the mechanical stimuli compared with the studied compositions. It means that the replacement of PETN by BCHMX improves the sensitivity of Semtex 1H to the mechanical stimuli. The data of the individual nitramines and both kinds of PBXs together relatively well correlated. A small dispersion in particular of the RDX, HMX and BCHMX data are caused due to the influence of the size and shape of their crystals on these sensitivities. A position of the individual PETN data in Fig. 2 is in expectation due to its high sensitivity to impact and friction.

On the other side, the detonation velocities measured were plotted in Fig. 3 versus the loading density of the prepared samples.

This relation is well known according to the theory of explosion. The results confirm the high accuracy of the results compared with each other. In addition, the velocity of detonation of Sem-BC+HMX is the highest compared with the composition studied. Also the addition of BCHMX as a replacement of PETN increased the detonation velocity of Semtex 1H by nearly 150 m/s. Semtex 1A has the lowest detonation velocity of the compositions due to the presence of PETN as the mainly energetic filler in addition to its low percentage in the composition (83 wt.%) compared with the other compositions in this study.

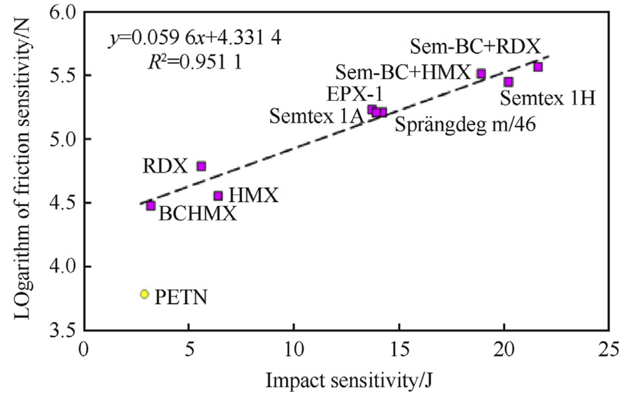

Fig. 2. A semi-logarithmic relationship between the sensitivities to impact and friction of the studied samples.

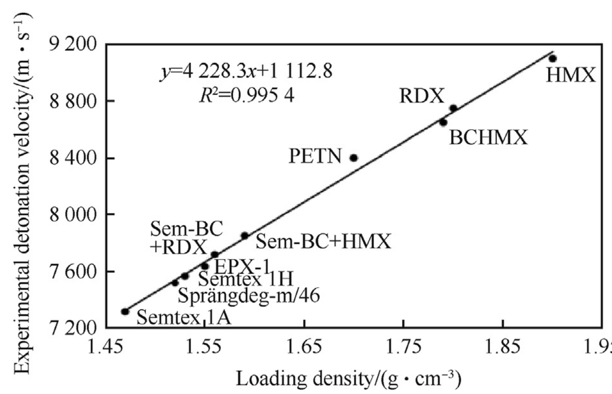

Fig. 3. A Relationship of the loading densities versus the experimental detonation velocities.

The calculated detonation parameters were compared with the experimental results in Fig. 4 where a relationship is presented between the detonation pressure calculated by EXPLOs code and the measured valued of ρD^2.

The good fitting between both the measured and the calculated values confirm the compatibility of EXPLO5 calculations with the measured ones. Also it confirms that the pressure of detonation of Sem-BC+HMX is the highest compared with the compositions presented in this work while Sem-BC+RDX has higher detonation pressure than Semtex 1H.

An interesting relationship was observed between the heat of combustion measured and the calculated heat of detonation

Table 3
The calculated detonation characteristics of the studied explosives.

No.	Explosive type	Density/$(g \cdot cm^{-3})$	EXPLO5			
			Velocity of detonation/$(m \cdot s^{-1})$	$\frac{D_{calc}-D_{exp}}{D_{exp}/100}$/(%)	Pressure of detonation/GPa	Heat of detonation/$(J \cdot g^{-1})$
1	Semtex 1H	1.53	7463	−1.4	20.33	5475
2	Sem-BC+RDX	1.56	7643	−1.0	21.41	5569
3	Sem-BC+HMX	1.59	7778	−0.9	22.80	5645
4	Semtex 1A	1.47	7014	−4.2	17.52	5099
5	Sprängdeg-m/46	1.52	7232	−3.8	19.28	5345
6	EPX-1 [26]	1.55	7398	−3.1	21.17	5542
7	PETN [3]	1.70	8350	−0.6	28.62	6258
8	RDX cryst. [3]	1.80	8718	−0.36	32.12	6085
9	HMX cryst. [3]	1.90	9225	+1.37	38.00	6075
10	BCHMX cryst. [3]	1.79	8840	+2.19	33.95	6447

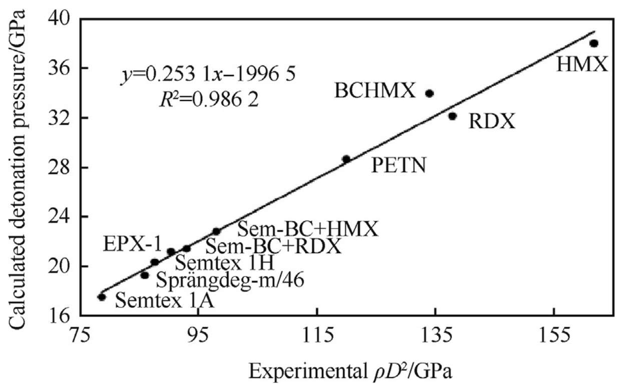

Fig. 4. A relationship of the pressure of detonation (calculated) and the measured values of ρD^2.

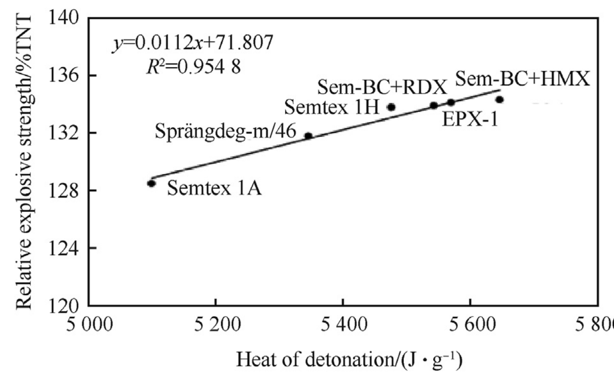

Fig. 6. Dependence of the explosives strength on their detonation heat.

obtained by EXPLO5 code as shown in Fig. 5.

Three groups were observed in this figure based on the obtained results. Group I includes the pure explosives except BCHMX and the traditional plastic explosives based on PETN. It is clear that increasing the percentage of the binder cause increasing of the combustion heat and decreasing of the detonation heat (inversely proportion relationship). This result confirms the significant influence of the binder system on the heat of combustion of the explosives (softened SBR in Semtex 1A has higher influence on the combustion heat than the viscous oil of Sprängdeg m/46 and the plasticized binder of EPX-1). While group II includes the studied samples based on Semtex 1H matrix and Semtex 1A. This group has very close values due to the presence of similar polymeric matrix which has significant effect on the heat of combustion while Semtex 1A is included due to the high percentage of polymeric matrix (17 wt.% polymer). This group has the highest values of the heat of combustion. The third group includes the pure BCHMX in addition to the plastic explosives include BCHMX as a part of its composition. This group showed the higher detonation heat of the studied compositions in addition to the pure explosives.

The values of the relative explosive strength of the studied compositions of explosives are presented in Table 2 while the dependence of these values on the detonation heat of the explosives is presented in Fig. 6. The results confirm that the explosive strength depends on the heat of detonation which represents the power of the explosive [34]. It was reported in Ref. [35] that the power of explosives depends on both the heat of explosion and the volume of gaseous products. This correlation confirms the influence of the explosive heat of detonation on its explosive strength. The plastic explosives, based on the Semtex 1H matrix, have very close explosive strength due to the similar wt.% of explosive in these mixtures. But still Sem-BC+RDX has higher value than Semtex 1H.

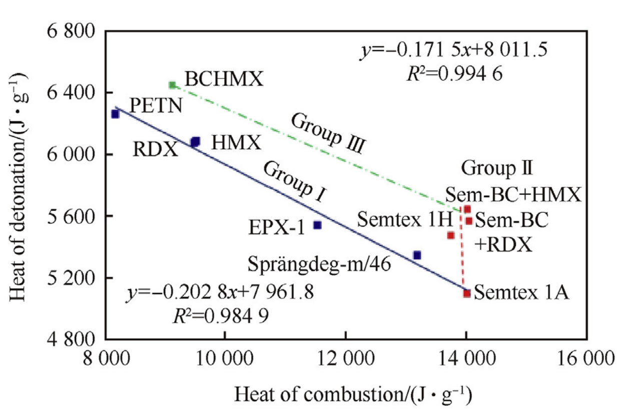

Fig. 5. The results of the heat of combustion measured in comparison with the heat of detonation calculated.

4. Conclusion

Replacement of penterythritol tetranitrate (PETN) by BCHMX in the well-known commercial explosive Semtex 1H leads to a remarkable enhancement in the detonation characteristics of the resulting plastic explosive (Sem-BCHMX-RDX). Besides, the sensitivities of this new plastic explosive to different stimuli were the lowest compared with the mentioned commercial plastic explosives. Regarding to the detonation characteristics, it was concluded that the best plastic explosive is the mixture with the replacement not only of PETN by BCHMX but also the replacement of RDX by HMX in Semtex 1H. Accordingly, the explosive strength of these advanced studied plastic explosives, determined by Ballistics mortar, is slightly higher than Semtex 1H and EPX-1. Also the type of the polymeric matrix was found to have significant effect on the heat of combustion of the studied explosive compositions. Briefly, the bottom line of this research confirms that the addition of BCHMX as a replacement for PETN in Semtex 1H produced a promising plastic explosive, which might be involved in industry.

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