COMPRESSIVE STRENGTH AND EXPLOSIVE CHARACTERISTICS OF POLYMER-BONDED EXPLOSIVES BASED ON HEXOGEN AND FLUOROELASTOMERS

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Abstract: *This paper describes the formulation of two polymer-bonded explosives based on RDX (hexahydro-1,3,5- trinitro-1,3,5-triazine) and fluoroelastomer binders by the water-slurry coating method. The fluoroelastomers are poly(VDF-HFP) (vinylidene fluoride-hexafluoropropene copolymer) and poly(VDF-CTFE) (vinylidene fluoride-chlorotrifluoroethylene copolymer). It has been observed that the impact sensitivity and the friction sensitivity of PBX samples were significantly lower than that of the single RDX. Results also showed that two PBX formulations have high chemical stability, high energy characteristics, and equivalent to some PBX in the world. Finally, the compressive strength of these PBX compositions was found in the range of 8-12 MPa.*

Keywords: Fluoroelastomer; Hexogen; Polymer-bonded explosive; The binder.

1. INTRODUCTION

Hexogen (also known as RDX) - a nitramine explosive chemically named hexahydro-1,3,5- trinitro-1,3,5-triazine - is one of the most widely used explosives in military and civilian applications because of its high energetic properties [1, 2]. However, the single RDX has some disadvantages (e.g. high sensitivity to mechanical shock and low compressibility). Therefore, RDX often used in the form of mixed explosives such as mixtures with other explosives, phlegmatized explosives and polymer-bonded explosives (PBX) [3-6]. In particular, the PBX based on a mixture of RDX and polymeric binder is a new explosive class with several advantages (e.g. high-performance characteristics, but low friction and impact sensitivity) and has been studied, manufactured and widely used in many countries such as Russia (ПВВ-5А, ПВВ-7), US (C-4, PBX-9205, PBX-9604), Spain (PG-3), Vietnam (C-4 VN, PBX-HP, PBX-HN) [7-9].

Most of the above PBX compositions have used binder systems based on several plasticized polymers such as polystyrene, polyisobutylene, styrene-butadiene rubber, hydroxy-terminated polybutadiene (HTPB), acrylonitrile-styrene-butadiene, polyurethane [1], *etc.* But these polymers were found to be ineffective for high-end applications because of certain limitations such as a limited shelf life under ambient conditions. On the other hand, fluorinated polymers have been found to possess properties that are better than those of other polymers. Fluorinated polymers such as poly(VDF-HFP) and poly(VDF-CTFE) have been found to be best suited for defense applications for making PBXs because of their chemical inertness, higher density, greater thermal stability and longer shelf-life [10].

This work aims at investigating several characteristics (e.g. impact sensitivity, friction sensitivity, chemical stability, brisance by Hess, detonation velocity, explosive strength, and compressive strength) of two PBX formulations along with a single RDX to evaluate the effectiveness of using fluoroelastomer-based binders in PBX compositions.

2. MATERIALS AND METHODS

2.1. Materials

The RDX class 1 (with the melting temperature ≥ 202.5 °C) was obtained from Z factory. Poly(VDF-HFP) is an elastomer with a fluorine content of 66%; a density of 1.81 $g.cm^{-3}$. Poly(VDF-CTFE) is an elastomer with a fluorine content of 50%; a chlorine content of 25.7% and a density of 1.86 $g.cm^{-3}$.

2.2. Methods

2.2.1. Sample preparation

PBXs formulations were prepared binders by the water-slurry coating method. Fluoroeslatomer samples (with sample masses of 5, 10 and 15 g) were dissolved in the appropriate solvent (acetone or ethyl acetate), maintaining the ratio of 1:20 (w/v), and kept for approximately 12 hours to obtain a homogeneous solution.

The explosive powder was added into the water in a reaction vessel, maintaining the explosive/water ratio of 1/10 (w/v), then the suspension was slowly heated up to 65 °C under the continuous stirring rate of 500 rpm. After that, the polymer concentration was added drop-wise with the stirring rate of 700 rpm to obtain a uniform dispersion of the binder over the explosive particle. When the adding process was completed, the mixture was continuously heated up to 80 °C at the same stirring rate for 30 min to evaporate the solvent completely. Finally, the product was cooled to below 30 °C and PBX samples were obtained via the vacuum filtration and dried in an oven at 60 °C. The compositions of PBXs are provided in table 1.

Table 1. *Compositions of PBXs based on RDX and fluoroelastomer.*

PBX composition	RDX (wt%)	Poly(VDF-HFP) (wt%)	Poly(VDF-CTFE) (wt%)
PBX-05F	95	5	-
PBX-10F	90	10	-
PBX-15F	85	15	-
PBX-05CF	95	-	5
PBX-10CF	90	-	10
PBX-15CF	85	-	15

2.2.2. Experimental techniques

- The impact sensitivity studies were carried out using Cast Hammer Impact Test with 10 kg drop hammer according to the TCVN/QS 1837:2017 (sample mass of about 0.05 g; the drop height of the weight is 250 mm).

- The friction sensitivity was determined using the BAM friction apparatus (provided by R&P GmbH, Germany) according to the STANAG 4487 standard [11] (sample mass of 10 mg). The smallest loading at which the initiation is observed at least once in six trials is reported as the test result.

- The chemical stability: The thermal vacuum stability was conducted by the vacuum stability test using a STABIL apparatus (OZM, Czech Republic) following the STANAG 4556-2A [12]. The sample mass was 2 g. Tests were performed at 100 ºC for 48 hours.

- The detonation velocity of the PBX samples was measured by an EXPLOMET-FO-2000 apparatus (Czech). The sample was prepared in the form of a cylinder with a 24 mm diameter and 320 mm length. Two optical sensors were placed at a distance of 250 mm. Charges of explosives were detonated using detonator No. 8.

- The brisance by Hess was measured according to the TCVN/QS 6421:1998 (with sample masses of 25 g and 50 g; density of charge is 1.0 g.cm^{-3}).

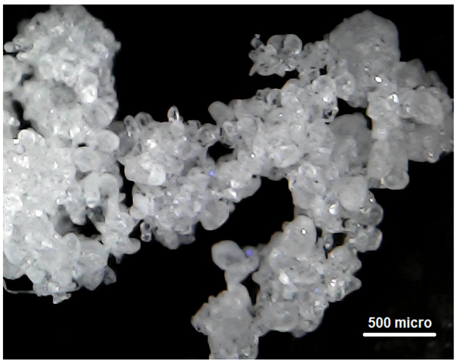
- The strength of explosives was measured by ballistic mortar according to the TCVN/QS 6424:1998 (sample mass of 10 g and density of 1.0 g.cm^{-3}).

- The compressive strength was determined using Universal Testing Machine ST-1000 (Salt Co.,Ltd, Korea). The compositions were compressed into a cylindrical charge with a diameter of 15 mm and a length of 20 mm (with the compression density of 1.60 g.cm^{-3}). The loading strain rate was 0.50 mm.min^{-1}.

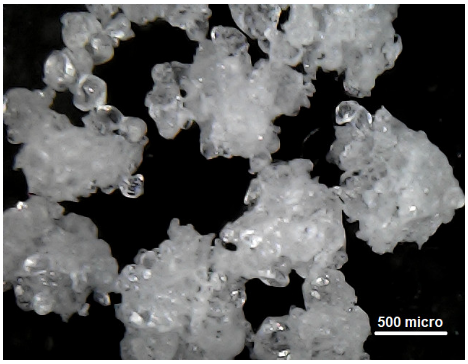
3. RESULTS AND DISCUSSION

3.1. The selection of organic solvent

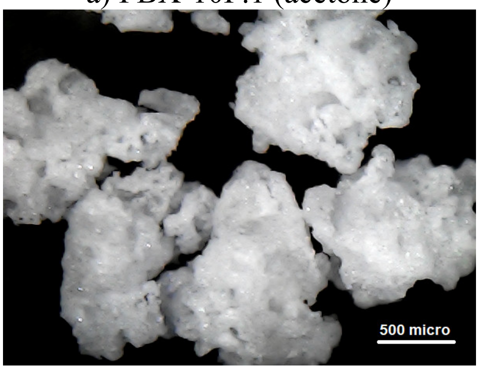
Organic solvents to be used in the water-slurry coating method are acetone and ethyl acetate due to both solvents have good solubility for fluoroelastomers. Polymer solutions using acetone and ethyl acetate as solvents were used to prepared PBX composition. The PBX sample quantity was determined by microscopic analysis. All PBX samples were photographed by microscope Nikon YS100 and digital camera. Microscopic photographs of PBX samples are shown in figure 1.



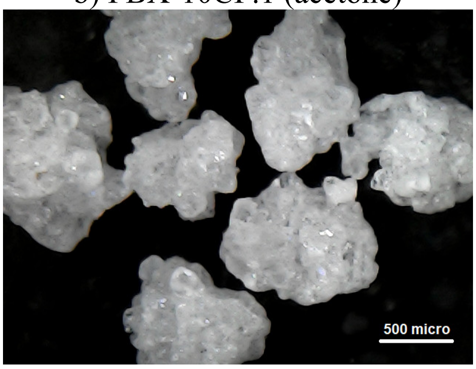
a) PBX-10F.1 (acetone)



b) PBX-10CF.1 (acetone)



c) PBX-10F.2 (ethyl acetate)



d) PBX-10CF.2 (ethyl acetate)

Figure 1. *Microscopic photographs of PBX samples.*

The samples PBX-10F.1 (Fig. 1-a) and PBX-10CF.1 (Fig. 1-b) were prepared by using acetone. Its quality was not satisfactory due to many uncoated RDX crystals within its structure and the binders were not homogeneously distributed in the sample. The samples PBX-10F.2 (Fig. 1-c) and PBX-10CF.2 (Fig. 1-d) prepared by using ethyl acetate have good quality. They have uniform-sized PBX granules and do not have uncoated RDX crystals. Therefore, the water-slurry coating method has yielded better RDX crystals coating when ethyl acetate was used as a solvent of fluoroelastomers.

3.2. The impact sensitivity, friction sensitivity, ignition temperature and thermal stability of PBX samples

Based on published studies about the PBX explosives [10, 13, 14] and the investigated results, it was found that: the PBX samples with the content of RDX higher than 95 wt.% had low adhesion, high impact and friction sensitivity. If the proportion of RDX was less than 85 wt.%, the PBX had low energy characteristics. Therefore, the RDX content range is between 85 to 95 wt.%.

In this work, the authors have focused on the effects of the proportion of RDX and the binder system to the impact sensitivity, friction sensitivity, ignition temperature and thermal vacuum stability. The results are shown in Table 2.

Table 2. *Effect of several factors on some characteristics of PBX samples.*

Sample	RDX content (wt.%)	Impact sensitivity (%)	Friction sensitivity (N)	Ignition temperature (°C)	Vacuum stability at 100°C/48h (mL.g^{-1})
PBX-05F	95	36	> 360 [a]	215.4	0.159
PBX-10F	90	20	> 360 [a]	216.2	0.145
PBX-15F	85	-	> 360 [a]	216.8	0.136
PBX-05CF	95	32	> 360 [a]	215.0	0.160
PBX-10CF	90	24	> 360 [a]	215.8	0.152
PBX-15CF	85	-	> 360 [a]	216.5	0.140
RDX	100	68	180	217.5	0.165
C-4 VN	91	28	> 360 [a]	216.2	0.185

[a] No reactions were observed up to 360 N load.

- *The impact sensitivities* of all PBX samples are significantly lower than that of single RDX. The reduction in impact sensitivity of PBX samples may be due to the RDX particles coated by the binder matrix, so the external mechanical impact may be absorbed and distributed more homogeneously, resulting in a reduced probability of initiation. On the other hand, the crystalline surface of RDX was partially dissolved when mixing in a binder solution, eliminating sharp edges and surface defects, reducing friction while influenced by the mechanical pulses.

From the results in table 2, it was found that the increase of RDX content would lead to an increase in the impact sensitivity of PBX samples. Because of the increasing content of RDX (i.e. reducing the content of the binder), the binder layer will be thin and inhomogeneous, thus, reducing the elasticity of the structure and increasing the impact of the mechanical pulse on RDX particles, resulting in increased sensitivity of PBX.

Besides, *the friction sensitivity* values of all PBX samples are also significantly lower than that of RDX. During the friction test, there was no reaction, even at maximum load (i.e. 360 N). This demonstrates that all PBX samples are safe during storage and transportation.

- *The ignition temperatures* of PBX samples are lower than that of single RDX. In PBX composition, the binder media created an isometric condition for RDX crystals to decompose when the PBXs samples were heated. The generated gas from the decomposition reaction of RDX increased the pressure within the binder media, hence accelerating the decomposition process of RDX crystals, leading to the early combustion of PBX [15]. On the other hand, the decreasing content of RDX leads to a slight increase in its ignition temperature.

- *The thermal stability:* It is noteworthy that the more gas released the lower chemical stability. All PBX samples have higher thermal stability than that of pure RDX. Besides, when increasing the content of RDX, the thermal stability of PBX tends to decrease. This can be explained by the fact that RDX has the lowest thermal stability in PBX composition. However, the thermal stability of all PBX samples is still significantly higher than the standard for the storage of explosives (2.0 $mL.g^{-1}$, STANAG 4556-2 [12]). Therefore, it can be confirmed that all of PBX samples have high thermal stability.

3.3. The detonation characteristics of PBX

To investigate the effect of several factors on detonation characteristics of PBX samples, several PBX compositions based on RDX and fluoroelastomers have been made and tested. The results are shown in Table 3.

Table 3. *Several detonation characteristics of PBX samples.*

Sample	**RDX content (wt.%)**	**Detonation velocity ($m.s^{-1}$) (at 1.50 $g.cm^{-3}$)**	**Strength of explosive, (% TNT)**	**Brisance by Hess at 1.0 $g.cm^{-3}$, (mm)**	
				25g	**50g**
PBX-05F	95	7620	133.7	21.0	Be destroyed
PBX-10F	90	7500	131.0	19.5	Be destroyed
PBX-15F	85	7365	-	-	26.5
PBX-05CF	95	7585	133.0	20.8	Be destroyed
PBX-10CF	90	7450	129.5	18.9	Be destroyed
PBX-15CF	85	7350	-	-	25.8
TNT	0	6655	100	-	15.6
RDX	100	7700	140-150	21.5	Be destroyed
C-4 VN (1.45 $g.cm^{-3}$)	91	7363	129.4	18.4	Be destroyed

From the results of table 3, it can be observed that the detonation characteristics (i.e. detonation velocity, brisance by Hess and strength of explosive) of all PBX samples (with the content of RDX in the range of 85-95 wt.%) are significantly higher than TNT and similar to the C-4 VN sample. Therefore, PBX samples belong to the high blasting explosive group. During the testing process, all of PBX samples have high sensitivity to the explosion impulse of detonator No.8.

3.4. The mechanical strength

As the weapons systems are exposed to a range of thermal and mechanical environments, it is important to characterize PBX compositions for mechanical properties. The mechanical strength of PBX samples depends on many factors such as particle size and its distribution, compression density, compressing condition, storage and test temperature [14], etc. In this work, all other constituent parameters were kept the same and the mechanical strength (i.e. the compressive strength) of PBX charges was assumed to depend on the binder characteristics. The compressive strength of PBX samples measured by Universal Testing Machine ST-1000 at ambient temperature is given in figure 2.

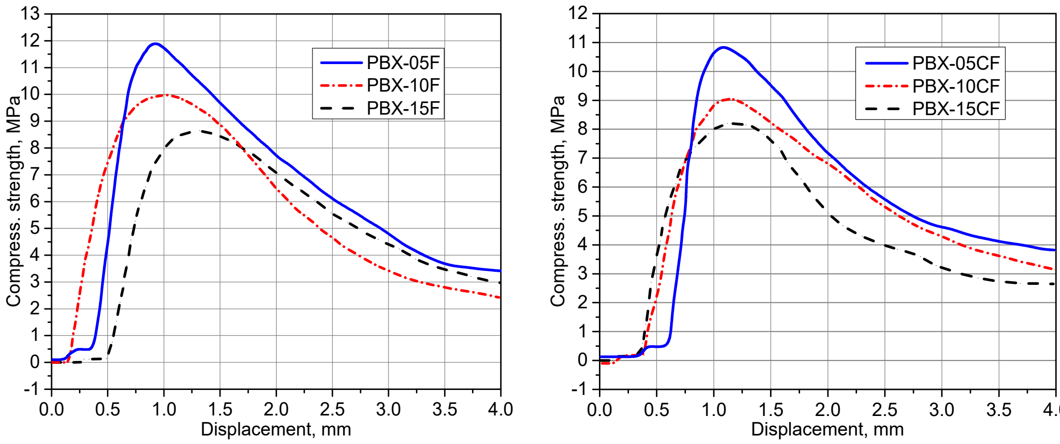


Figure 2. *The compressive strength of PBX samples based on RDX and fluoroelastomers.*

From figure 2, it can be observed that PBX samples with the same fluoroelastomer content have similar compressive strength and within a range of 8-12 MPa. In particular, these compressive strength values of PBX compositions are also in good agreement with those of similar explosives reported by A. Singh et al. [14] and D.G. Thompson et al. [16].

4. CONCLUSION

Ethyl acetate is a suitable solvent for the water-slurry coating technique for processing of PBX formulations based on RDX and fluoroelastomers, given better-coated PBX granules than the using of acetone. PBX compositions based on RDX (with the RDX content of 85-90 wt.%) and fluoroelastomer (i.e. poly(VDF-HFP) and poly(VDF-CTFE)) have low impact and friction sensitivity, high chemical stability, high energy characteristics, equivalent to some of available PBX formulations in the world such as C-4, C-4 VN. Besides, the PBX samples in this work have good compressive strength, can be used as explosive boosters as well as loaded in some types of ammunition.

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TÓM TẮT

ĐỘ BỀN NÉN VÀ CÁC ĐẶC TRƯNG CHÁY NỔ CỦA THUỐC NỔ PBX TRÊN CƠ SỞ HEXOGEN VÀ CAO SU CHỨA FLO

Bài báo mô tả công thức của hai nhóm thuốc nổ PBX trên cơ sở RDX (hexahydro-1,3,5- trinitro-1,3,5-triazine) và chất kết dính cao su chứa flo được chế tạo bằng phương pháp phủ trong môi trường nước. Các chất kết dính polymer được sử dụng gồm poly (VDF-HFP) và poly (VDF-CTFE). Kết quả nghiên cứu cho thấy, độ nhạy với xung cơ học của các thuốc nổ PBX thấp hơn đáng kể so với thuốc nổ RDX nguyên chất. Mặt khác, hai loại thuốc nổ PBX đã chế tạo có độ bền hóa học và có các đặc trưng năng lượng cao, tương đương với một số thuốc nổ PBX phổ biến trên thế giới. Cuối cùng, độ bền nén của các thuốc nổ PBX kể trên nằm trong khoảng 8-12 MPa.

Từ khóa: Cao su chứa flo; Hexogen; Thuốc nổ PBX; Hệ chất kết dính.

Received 14th February 2020
Revised 10th April 2020
Published 6th May 2020

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