International Journal of Advanced Materials and Production Vol.1, No. 1, December, 2016

Synthesis and Characterization of Advanced PBXs Materials Based on GAP and HTPB

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Abstract. This paper describes formulations of plastic bonded explosives (PBXs) based on three highly brisant explosives, namely (RDX, PETN, and HMX) with polyurethane (PU) based on Glycidyl azide polymer (GAP) as an energetic binder and hydroxy terminated polybutadiene (HTPB) as an inert binder in comparison with composition-B, which used in the fragmentation warheads. The performance properties of PBXs were evaluated by both thermochemical calculations and experimental results of prepared selected PBX compositions. Performance parameters of the selected PBXs were evaluated by using the EXPLO5 computer program. The sensitivity and performance properties of different types of PBXs were evaluated by experimental results of prepared selected PBX compositions. Casting technique was used to prepare the selected compositions containing 14% PU based on GAP and HTPB. The results of the prepared selected compositions were emphasized by the thermochemical calculations. It has been observed that the brisance of the PBX based on HMX and GAP was higher than that of comp-B by 21.3 %, the detonation velocity showed a remarkable increase of the order of 8480 (m/s) while that of comp-B was 7638 (m/s). A controlled fragmentation warhead with an outer grooving warhead case of dimensions 100x35x4 mm was used and arena test was carried out to determine the lethal zone of the fragmentation warhead. The lethal zone obtained from arena test for PBX composition based on HMX and GAP named PBXHG4 was higher than the other prepared PBX formulations based on GAP and than that of comp-B by 40%.

Keywords: *Plastic bonded explosives; HMX; RDX; PETN; HTPB; GAP; Comp-B; Thermochemical calculations; EXPLO-5.*

I. Introduction

The new development in the field of explosives is to develop plastic bonded explosives (PBXs) which have significantly lower vulnerability to various stimuli than conventional high explosives as comp-B that suffers from various disadvantages such as relatively poor impact sensitivity, cure shrinkage which results in voids and cracks, and somewhat violent reaction during cook-off [1-3]. By the end of the First World War, the explosives development takes the direction to improve the explosive performance, and as a result, the sensitivity of explosives has been increased. Over the years, many accidents were happened during handling, transporting, testing and manufacturing of explosives, where many researchers have always paid attention to increase performance without considering safety aspect. The demand for increased safety in explosives transportation, handling, and storage has led to the improvement of Insensitive Munitions (IM) [4]. The design of these weapons and explosives decreases the probability of unwanted and unexpected detonation from external stimuli such as weapon fragments, heat, and shock. This can be achieved by the modification to the explosive formulation.

Plastic bonded explosive (PBXs) are various explosive mixtures where the crystals of high explosives are embedded into a thin layer of polymeric material. Recently, many researches focused on the preparation, characterization and applications of modern of PBX formulations based on high brisance explosives and energetic polymeric binders to achieve better explosive properties and low vulnerability [5-8]. Controlled fragmentation warheads are used to defeat almost all types of

Manuscript received July 1, 2016; revised August 1, 2016; accepted September 1, 2016.

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targets (underwater, aerial, human and underground) to set them out of action by the action of fragments created from the warhead body at the time of explosion. The velocity of fragments depends mainly on the detonation velocity or brisance of the high explosive. Higher fragment velocity and large lethal zone could be obtained by using high performance explosive material [9,10].

In this work the performance of different types of PBXs was evaluated by both thermochemical calculations and experimental results of prepared selected PBX formulations that use a mixture of high explosives and different types of either inert or energetic binders to choose PBX formulations which satisfy the required performance parameters needed for fill some advanced applications.

II. Thermochemical Calculations

EXPLO5 program was used for calculation of detonation parameters, while the explosion force (F) and brisance (B) were calculated by empirical formulas. The input data required to run the program are the density and percentage of each component in the explosive formulation. Samples abbreviation of used PBX formulations are shown in Table 1, while the explosive characteristics (density, detonation velocity, explosion force and brisance) of comp B and PBX formulations based on RDX, HMX and PETN with polyurethane based on either HTPB or GAP are shown in Table 2. Results of thermochemical calculations are very important for explosive formulations that are candidate for preparation and expected to give the required performance of the needed application.

Table 1. Samples abbreviation of PBX formulations

PBXs abbreviation \ Wt (%)	RDX	HMX	PETN	PU (HTPB)	PU (GAP)
PBXRT4	86	-	-	14	-
PBXHT4	-	86	-	14	-
PBXPT4	-	-	86	14	-
PBXRG4	86	-	-	-	14
PBXHG4	-	86	-	-	14
PBXPG4	-	-	86	-	14

A. Density (ρ)

Density increases by pressing or casting which improves the detonation velocity and brisance of the explosive formulations. The density of the calculated PBX formulations decreases as the weight percentage of PU increases as shown in Fig.1 and Fig. 2. For PBXHT4, density decreased by ≈ 8.3% compared with pure HMX but for PBXHG4 it decreases by ≈ 5.2% compared with pure HMX. PBX formulations based on PU (GAP) were denser than that based on PU (HTPB). From Fig. 3, it is clear that the explosive formulation PBXHG4 gave the highest density.

B. Detonation Velocity (D)

Detonation velocity represents a great importance in the fragmentation warheads because there is a relation between the detonation and Gurney velocities [11,12]. Detonation velocity of the PBX formulations decreases as the weight percentage of PU increases which confirms that PU is not a reaction partner in the detonation zone. For PBXHT4, detonation velocity decreased by ≈ 9.4% from pure HMX but for PBXHG4 it decreased by only ≈4.9% from pure HMX, Fig. 4 and Fig. 5. This may be attributed to energetic groups (Azide groups, oxygen atoms) of GAP and hence its conversion rate is higher than that of HTPB, which contains only carbon and hydrogen atoms. From Fig. 6, it is clear that the formulation PBXHG4 give the highest detonation velocity.

C. Explosion Force (F)

Explosion force represents the output work capacity of the decomposition gaseous products. It is also an important parameter in the calculation of brisance. The explosion force is calculated by [13]:

$$F = n\, R\, T_v$$

Or

$$F = 371.15\, V_o\, T_v$$

F Explosion force [J/kg]
T_v Explosion temperature [K]
n Number of moles of gaseous products / 1kg of the explosive
R Universal gas constant = 8.3145 [J/ (mol.K)]

Explosion force of the PBX formulations decreases as the weight percentage of PU increases as shown in Fig. 7 and Fig. 8. From Fig. 9, it is clear that the formulation PBXRG4 give the highest explosion force.

D. Brisance (B)

Brisance of an explosive is a very important parameter which represents the ability of explosives to disintegrate the solid object surrounding the explosive charge and produce fragments from this object. The brisance of an explosive depends mainly on explosive density, detonation velocity, composition of gaseous products and explosion temperature. The brisance is calculated by Kast equation [13]:

$$B = F\, \rho\, D$$

B Brisance [N/ (m.s)]
ρ Density [kg/m^3]
F Explosion force [J/kg]
D Detonation velocity [m/s]

Brisance of the PBX formulations decreases as the weight percentage of PU increases as shown in Fig.10 and Fig.11. For PBXHT4, the brisance decreased by 26.7% compared with that of pure HMX. This decrease is related to the decrease of the brisant high explosive content (HMX) and hence the decrease of oxygen balance (more negative), number of moles of gaseous products and detonation velocity of the prepared PBX formulations. A better situation was obtained for the formulations based on GAP; the values of brisance were decreased, for PBXHG4, the brisance decreases by 13.8% compared with that of pure HMX. The values of brisance for formulations based on GAP are higher than those of corresponding compositions based on HTPB. GAP is a more energetic binder than HTPB due to better oxygen balance and higher calorific value. From Fig.12, it is clear that the PBXHG4 give the highest brisance.

Table 2. Explosive characteristics of Comp-B and PBX formulations

PBXs abbreviation \ Properties	ρ [gm/cm^3]	D [m/sec]	F [kJ/kg]	Brisance [N/m.sec] *10^{-13}
RDX	1.82	8913	1262	2.04
HMX	1.91	9200	1237	2.17
PETN	1.76	8487	1225	1.83
PBXRT4	1.68	8053	1098	1.49
PBXHT4	1.76	8333	1081	1.59
PBXPT4	1.65	7807	1072	1.38
PBXRG4	1.74	8462	1196	1.76
PBXHG4	1.82	8746	1175	1.87
PBXPG4	1.7	8192	1166	1.63

III. Experimental

A. Preparation of Plastic Bonded Explosives

All the chemicals used in this work; RDX, HMX, PETN, GAP, HTPB, DOZ, MAPO and Isophoron diisocyanate (IPDI - crosslinking agent) were of high purity. These PBXs formulations based on polyurethane were prepared by using the casting technique under vacuum [14]. This process was conducted in a stainless steel bowl of 5 kg capacity provided with double wall jacket, where a circulating liquid could be either heated or cooled. Stainless steel bowl is equipped with a vertical mixer with three blades rotating in an orbital motion. The prepolymers used in this work were HTPB and GAP (HTPB of 0.85 and GAP of 1.43 measured mg equivalent OH/g HTPB and GAP respectively) the plasticizer (DOZ) and bonding agent (MAPO) were used with HTPB only. The prepolymer was precisely dropped into the reactor and then preheated until the temperature reaches to 60 ^oC then the dried pure explosive was divided into four equal portions and added during stirring without vacuum for 8 minutes for every portion. After adding the fourth portion of the explosive, the mixer was kept under vacuum for 18 minutes to avoid the presence of air bubbles in the mixing samples. Finally, the curing agent (IPDI) was added and mixing was carried out for relatively short time. The explosive mixture was then poured in polyvinyl chloride (PVC) mould tubes and experimental controlled fragmentation warhead to measure detonation velocity and lethal zone respectively after curing which was carried out at 55-60 ^oC for 12 days. Six PBX formulations (86% explosive + 14% binder) were prepared as shown in Table.1.

B. Evaluation of PBXs Formulations

1) Sensitivity tests

Sensitivity to friction was determined using BAM friction test apparatus. The frictions test was determined by the percentage of initiation by changing the loading of the pistil [15]. Sensitivity to impact was carried out using IKa Maschinenbau apparatus, using 5 Kg falling weight [16]. Upper sensitivity limit was used to identify the minimal height at which 100% initiation was achieved. The sensitivity to heat was obtained by measuring the ignition temperature for the prepared PBX samples using Chilworth deflagration test apparatus [15]. To determine the ignition temperature, the temperature was uniformly increased [5 ^oC/min] until the explosion conversion occurred.

2) Detonation velocity

The prepared PBX samples were pressed to a density 1.6 (g/cm^3) in PVC tubes of 2 mm inside diameter and 190 mm length. The Exploment -Fo-2000- Multi Channel (Swiss made) was used to measure the detonation velocity of these formulations. The time interval for a detonation wave to travel a known distance between the two fiber optic probes in microseconds was displayed with the calculated detonation velocity in (m/s) [17].

3) Brisance

This test was carried out using the brisance testing unit according to Kast technique [15], where 2.5 g of the explosive charge was pressed to a density of 1.6 (g/cm^3) into an aluminum tube of 30 mm height, 12 mm inside diameter and 4 mm wall thickness. Special test detonator with 0.2 g of lead azide and 0.4 g of RDX was prepared on site to initiate the explosive charge. The copper crushers used are of 9.8 mm height and 6 mm diameter. The deformation (final lengths) of copper crushers was determined after the explosion of the charges and converted into force units according to the calibration table of the copper crusher static compression force test [18].

4) Arena Test

The arena test is used to measure the effects of high-explosive warhead detonations to determine the lethal zone. Lethal zone is one of the most important parameter of HE warhead efficiency [19]. The used controlled fragmentation warhead of dimensions (100 mm length, 35 mm diameter and 4 mm thickness) made from steel 35 as shown in Fig. 13, was selected to be filled with 100 g of the investigated PBX formulations. In this test, we compare lethal efficiencies for similar warheads; the warhead is put on the ground at which the warhead nose is in the down position in the center of the test arena. The target is made of metallic witness panels of dimensions (2 m height, 1 m width and 2 mm thickness) placed at specified distances (10, 15, 20, 25, 30 and 35 m) from tested warhead. Electric detonator was used to initiate the high explosive charge, after the detonation of the warhead, number of perforations at metallic witness sectors are counted per square meter for each sector. A characteristic distance is the fragments concentration density of one perforation per square meter. This distance is named warhead efficiency radius, which means that warhead with greater lethal zone has corresponding greater efficiency radius [20,21].

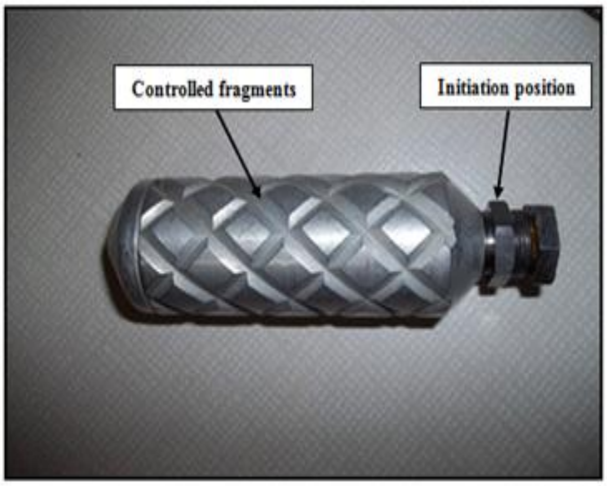

Figure 13. Photograph of the used controlled fragmentation testing cylinder casing.

IV. Results and Discussion

A. Sensitivity Tests

For comp-B (60% RDX + 40% TNT), and the prepared PBX formulations, the sensitivity results are listed in Table 3. It is clear that for PBXHG4, the decrease of sensitivity to impact was 42.5% compared with comp-B. PBXRG4 and PBXHG4 showed no initiation even when applying the maximum friction force (360 N) of the test apparatus but PBXPG4 showed initiation because of PETN is high sensitive to friction. PBXs showed ignition temperature slightly lower than comp-B. This can be attributed to the fact that the coating of polyurethane based on GAP acts as heat sensitizing medium because its softening temperature is less than 152 ^{o}C. PBXHG4 has sensitivity to heat close to that of comp-B. The values of ignition temperature for the prepared PBX formulations and comp-B are listed in Table 3.

B. Detonation Velocity

The detonation velocity of explosives is one of the important terms which represent the rate of energy delivery through explosive conversion. From the obtained results we can find that the type and content of binder have a significant effect on detonation velocity of the prepared PBX formulations. The values of detonation velocity (D) were determined for comp-B and the prepared PBX formulations are listed in Table 3. For PBXRG4, detonation velocity increased by 6.9% but increased by only 3% for PBXPG4. For PBXHG4, the increase of detonation velocity was 11%, when compared with that of comp-B.

C. Brisance

The values of brisance (B) were determined for comp-B, and the prepared PBX formulations are listed in Table 3. Brisance were slightly increased for PBXPG4 by 6.9 % and for PBXRG4 increased by 9.2%, for PBXHG4 the increase of brisance was 21.3%, when compared with that of comp-B, which mean a great improvement in shuttering effect, improved velocity of the fragment and the lethal zone.

Table 3. Sensitivity and performance results of comp-B and PBX formulations based on PU (GAP).

Explosive	Impact (J)	Friction (N)	Ignition Temp. (°C)	Detonation velocity (m/s)	Brisance (kp)
Comp-B	12.0	220	239	7638	1059
PBXRT4	22	>360	230	7898	1137
PBXHT4	19.1	>360	253	8035	1209
PBXPT4	17.7	256	243	7712	1088
PBXRG4	19.8	>360	232	8165	1157
PBXHG4	17.1	>360	234	8480	1285
PBXPG4	15.3	238	228	7867	1132

D. Arena Test

The lethal zone is one of the most important parameters of high explosive warhead efficiency. The warhead lethality zone for comp-B and the prepared PBX formulations based on PU (GAP) are shown in Fig. 14. Only one fragment is sufficient to kill or affect on the target so, a horizontal line was sketched at fragment density = 1 and the radius of lethality zone for each examined explosive charge was obtained from the X axis. It is clear that warhead filled with PBXHG4 has a greater lethal efficiency (28 m) than PBXRG4 (25 m), PBXPG4 (23 m) and comp-B (20 m). For PBXHG4 the increase of efficiency radius was 40%, when compared with that of comp-B. From Fig. 15, it is clear that fragments sizes were controlled as regular and effective from warhead casing to avoid its random distribution which could be achieved by grooving the outer surfaces of the warhead casing. After the explosion of the warhead; the explosion force affect on the weak positions in the warhead structures which are located between the formed fragments and produce a controlled fragment size and shape.

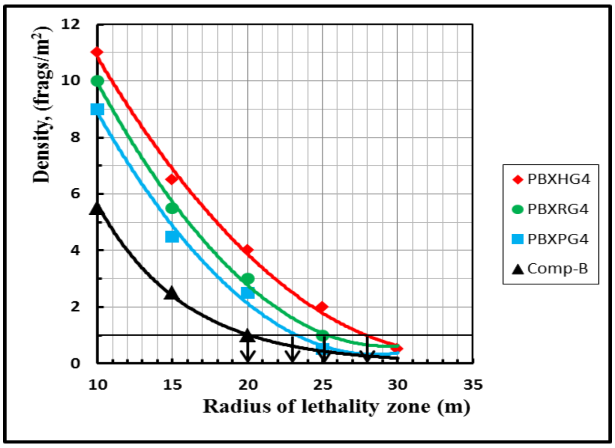

Figure 14. Warhead lethality zone of the warhead filled with comp-B and PBX formulations based on GAP.

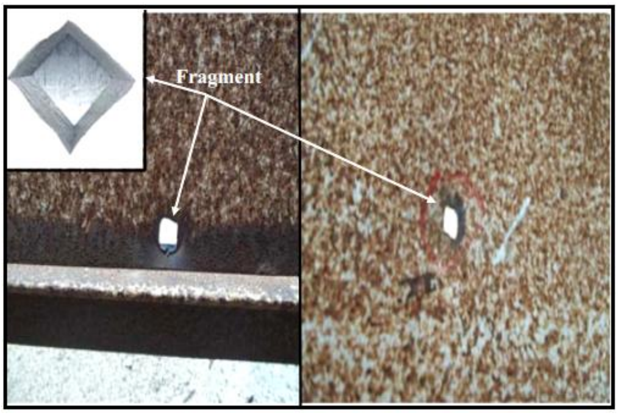

Figure 15. Photograph of the controlled fragment after the detonation of the warhead and its effect on the witness sectors.

V. Conclusions

In the present study, Six PBX formulations based on 86% explosive material (RDX, HMX, and PETN) and 14% binder (PU based on GAP or HTPB) have been formulated using casting technique and investigated for explosive and performance properties by both thermochemical calculations and experimental results. The choice of this technique increases the safety during production. The measured sensitivity characteristics proved that PBXHG4 has lower sensitivity to the mechanical stimulus (impact, friction) than that of comp-B by 42.5% for impact sensitivity. Its sensitivity to heat is close to that of comp-B. PBXHG4 has higher performance parameters, in which detonation velocity increased by 11%, brisance increased by 21.3% and lethal zone increased by 40% when compared with that of comp-B. PBXs possess several advantages: ease and simplicity of production, lower sensitivity to impact and friction, suitable heat sensitivity, performance and increased safety. Thus, it can be said that these formulations especially PBXHG4 which have high values of brisance, are recommended to be used as a main explosive charge of low sensitive fragmentation warheads and demolition charges instead of composition-B.

VI. Appendix A Thermochemical calculation results

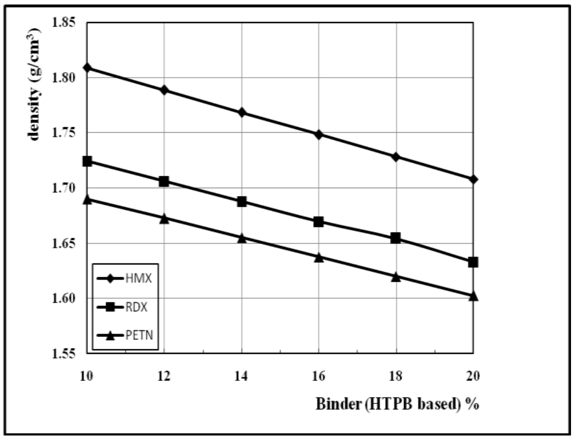

Figure.1 Effect of binder percentage (based on HTPB) on the density of PBX formulations

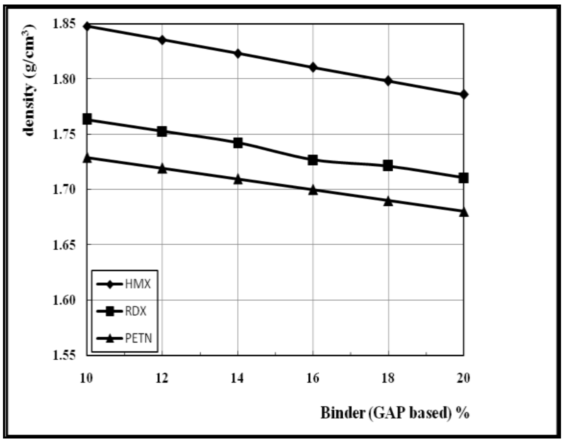

Figure.2 Effect of binder percentage (based on GAP) on the density of PBX formulations

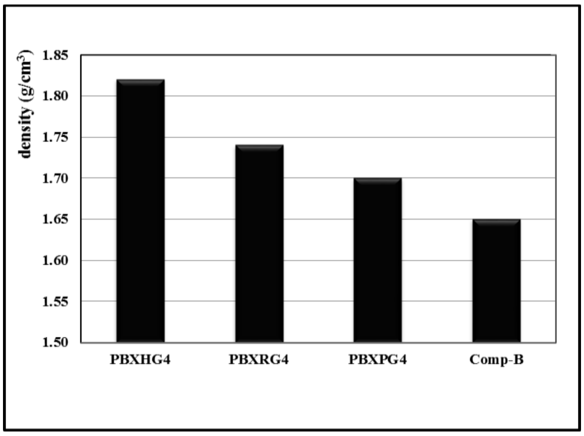

Figure.3 The density of PBX formulations based on 14% PU (based on GAP) and comp-B

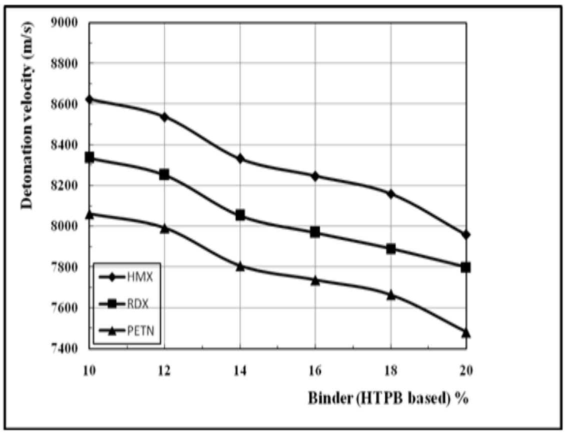

Figure.4 Effect of binder percentage (based on HTPB) on the detonation velocity of PBX formulations

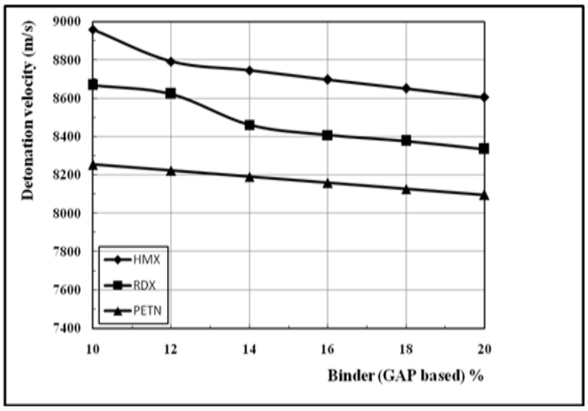

Figure.5.Effect of binder percentage (based on GAP) on the detonation velocity of PBX formulations

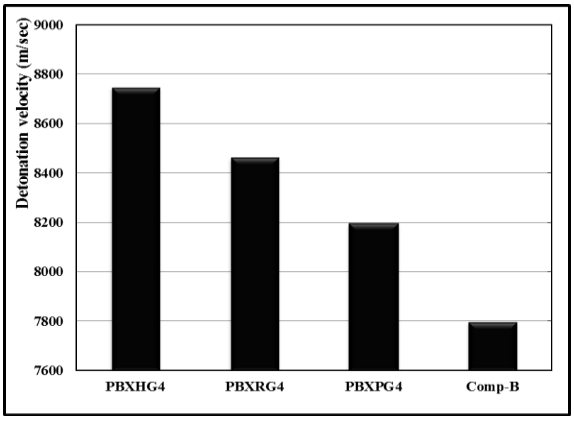

Figure.6 The detonation velocity of PBX formulations based on 14% PU (based on GAP) and comp-B

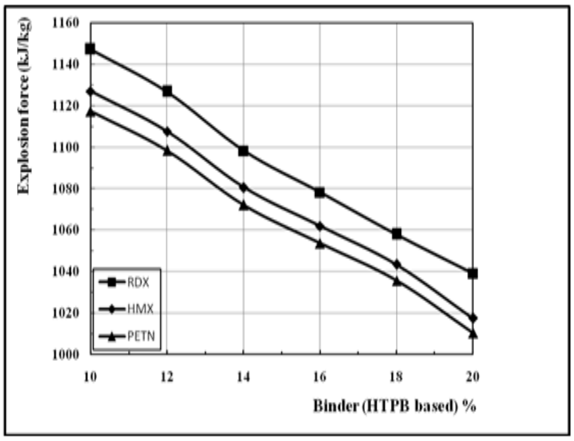

Figure.7 Effect of binder percentage (based on HTPB) on the explosion force of PBX formulations

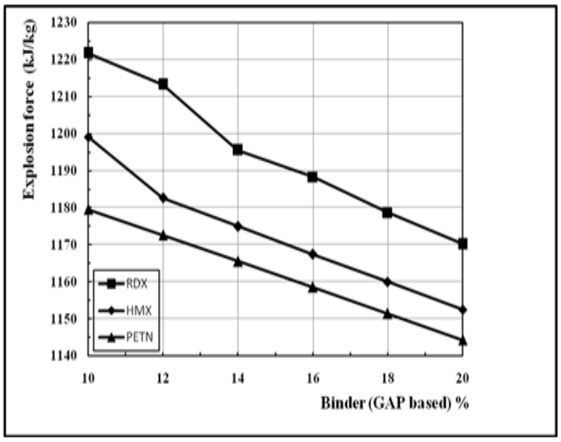

Figure.8 Effect of binder percentage (based on GAP) on the explosion force of PBX formulations

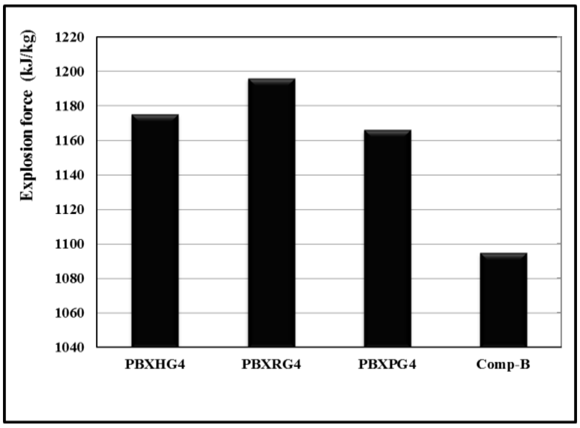

Figure.9 The explosion force of PBX formulations based on 14% PU (based on GAP) and comp-B

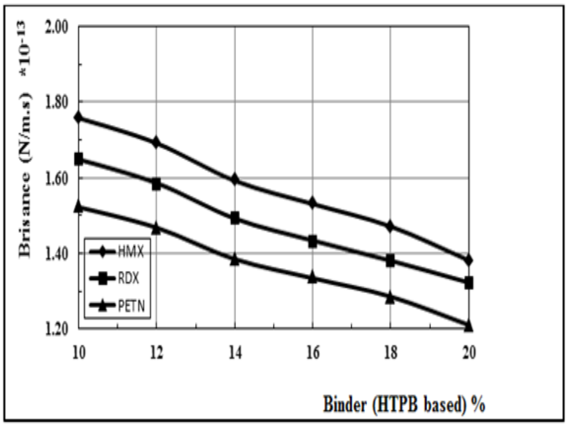

Figure.10 Effect of binder percentage (based on HTPB) on the brisance of PBX formulations

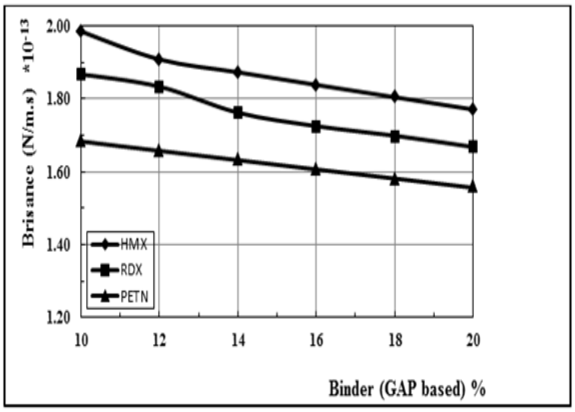

Figure.11 Effect of binder percentage (based on GAP) on the brisance of PBX formulations

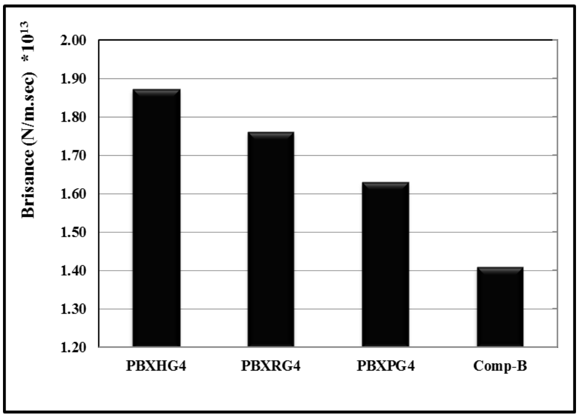

Figure.12 The brisance of PBX formulations based on 14% PU (based on GAP) and comp-B

VII. Acknowledgment

We would like to extend thanks to the people whose contributions helped make this research and the group that we worked closely with. They have always been there to answer questions or give advice when we have difficulties. Also, we would like to thank School of Chemistry and Environment, Beijing University of Aeronautics and Astronautics to provide the instruments and its technical support.

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