Theoretical and experimental study of underwater explosion performance of selected explosive compositions

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Theoretical and experimental study of underwater explosion performance of selected explosive compositions

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Abstract: Measurements of underwater explosion parameters and their effects are still the major problem for naval designer. In this study, thermo-chemical calculations have been carried out using EXPLO5 code to determine the underwater explosion parameters for different selected explosive mixtures. Preparation of the different types of explosive mixtures based on melt cast explosive (TNT) and plastic bonded explosives (PBXs) based on polyurethane binder system were presented. The effect of different aluminum weight percentage for the selected explosive mixture has been investigated with respect to the impulse and the resulted deformation. Underwater experimental measurements of the prepared explosive mixtures based on steel plate's deformation were determined and compared. It was concluded that PBX based on RDX in addition to 25 wt% aluminum and 30wt% ammonium perchlorate produces the highest underwater explosion performance from all the tested samples. This explosive mixture is candidate to replace the traditional well known TNT in the underwater explosive applications.

Keywords: explosives, underwater explosion, performance, gas bubble.

1. Introduction

The mechanical properties of materials and their efficiency to bear large plastic deformation before its fractures are major parameters in underwater structural applications [1,2].
Many researchers undergo different experimental studies to measure the large deformation for plates subjected to different blast loading [3-5].
Underwater explosion have been described as the conversion of the explosive material into hot gases with high pressure and temperature [6]. The arrival of the detonation wave to the water boundary layer produce shock wave followed by the effect of the gas bubble expansion [7,8].The energy content of explosive mixtures can be divided into three main parts, namely, shock wave energy, bubble energy, and heat energy loss due to the water compression. The ratio of the three parts can govern the naval application for the explosive mixture [9,10]. Different types of explosives can be used for underwater explosion. Melt cast explosives based on Trinitrotoluene (TNT) can be used [11-13]. The performance and sensitivity of several plastic bonded explosives (PBXs) based on high energy materials are important parameters for underwater charges [14-16]. In addition, aluminized explosives were studied for application of underwater explosion [17-21]. Recently; several advanced explosives have been prepared. Sensitivity, thermal stability and detonation parameters of these explosives have been

published [22-24]. The possibility of applying these explosives for underwater applications has not been published yet.
New field of research have been established when underwater explosion propagate and cause different lethal damage to submerged structures. Many researchers have demonstrate the first work which was done on underwater explosion as it concentrated on the first underwater explosion effect which is shock wave effects [25,26]. The First World War made the research on the field of underwater explosion faster by measuring the pressure-time history and the development of the gas bubble [27]. Arons showed the advance in measuring the underwater pressure time curve non-contacted under water explosion is one of the basic problems for structure designer which give more importance for understanding the deformation and failure mechanism of these structures.
In this study, we tested steel plate subjected to non-contact underwater explosions with a suitable setup. At first, thermo-chemical calculations have been carried out using EXPLO5 code to obtain the most suitable compositions for this study followed by theoretical calculation to its underwater explosion performance parameter of the selected explosive mixtures. Preparation of the different explosive mixtures was discussed. Therefore, the explosion of 1kg of conventional high explosive (TNT) charge was used for comparison with other explosive compositions in addition to its importance for scaling. The energy output of this explosive is enhanced by adding active metallic additive as aluminum with different percentage. The study is focusing on the underwater explosion performance parameter of the selected explosives mixture using steel plate deformation.

2. Analytical studies for underwater explosion calculations

Underwater explosion performance of all the explosive compositions can be calculated and scaled according to its TNT equivalent [28]. The shock wave energy and maximum peak pressure can be calculated according to the following equations (1) and (2):

$$Pm = 52.16\left[\frac{W^{1/3}}{S}\right]^{1.13} \quad (1)$$

$$Esw = 98000\left(W^{\frac{1}{3}}\right)\left[\frac{W^{\frac{1}{3}}}{S}\right]^{2.1} \quad (2)$$

Where W is expressed in kg of TNT and s is the stand-off distance measured in meter.
The decay time constant Θ in micro second can be measured by the following equation (3):

$$\theta = 96.5\left(W^{\frac{1}{3}}\right)\left[\frac{W^{\frac{1}{3}}}{S}\right]^{0.22} \quad (3)$$

The degree of shock damage can be estimated by the shock factor values. The shock factor at the point of the target nearest the charge is computed from equation (4).

$$\text{SF (exp)} = \frac{\sqrt{W_{TNT}}}{d} \quad (4)$$

The first bubble pulsation period can be calculated theoretically by the following equation:

$$\mathrm{T} = 2.08\left(\frac{\mathrm{W}^{1/3}}{\mathrm{Z}^{5/6}}\right) \quad (5)$$

Where, Z equal D+10 and represents the total static pressure at the location of the explosive and D is the depth of the explosion in m [28].
The maximum bubble radius can be estimated by this equation (6):

$$A_M = [\frac{13QW}{H+10}]^{1/3} \quad (6)$$

Where;
Q is the heat of explosion (MJ/kg), W is the mass of explosives (kg) and H is the sum of the hydrostatic pressure at the charge depth in unit of m of water [27]. The following dimensionless numbers (ϕ) as a function of the free field impulse (I) for underwater explosion can be calculated by the following equation:

$$\phi = \frac{\mathrm{I}}{2t^2}\frac{1}{(ab\rho\sigma)^{1/2}}\,a\,b \quad (7)$$

Where t is the thickness of the plate,ρ is the density of the plate, σ is the static yield stress, a,b is the length and width of the plate [29]. We can calculate the deformation occurred to the plate using equation (8):

$$\frac{D}{t} = 0.553\phi + 0.741 \quad (8)$$

Where D is the deformation, t is the thickness of the plate and ϕ is dimensionless numbers calculated by the mentioned equations. Keil shows the contact explosion damage relation which involved the radius R of the hole and the explosive mass W, on a plate of thickness t [30].

3. Theoretical calculations of explosives performance underwater

The theoretical detonation characteristics (heat of explosion Q_v) for all experimentally tested explosives were calculated using the EXPLO5 code and the mass of the TNT equivalent (W_{TNT}) can be estimated by calculating the ratio of Q_{EXP}/Q_{TNT}. Table (1) represent the tested explosive compositions and table (2) represent the explosion heat (Q_v), TNT equivalent (W_{TNT}) and the calculated shock factor (SF) for all tested explosive mixtures.

Table (1) Composition of the prepared explosive mixtures

code	**Explosive Type (wt%)**					
	HMX	**RDX**	**Al**	**TNT**	**AP**	**PU**
TNT	-	-	-	100	-	-
TR	-	42	18	40	-	-
TH	42	-	18	40	-	-
PH1	75	-	10	-	-	15
PAP	-	30	25	-	30	15

Table (2) characteristics of the tested explosive mixtures

Compositions	**TNT**	**TR**	**TH**	**PH1**	**PAP**
Q_v(Mj/kg)	5.140	8.27	8.26	7.04	8.422
W_{TNT}	1	1.61	1.6	1.37	1.63
SF	3.57	4.81	4.79	4.49	4.81

3.1. Peak Pressure for explosive mixtures

Figure (1) represents the peak pressure resulting from the explosion of the tested explosion formulations based on RDX, HMX, AP and TNT as reference explosives. The resulted peak pressure represents the output specific impulse which is very important parameter in underwater explosion performance along the time history of the UNDEX.

It is clear from the figure that the output peak pressure of the underwater explosives increases as the weight percentage of Al increases. This increases in peak pressure due to the increases of the energy content of the explosives compositions which represented by the heat of explosion and the number of moles of gaseous detonation product.

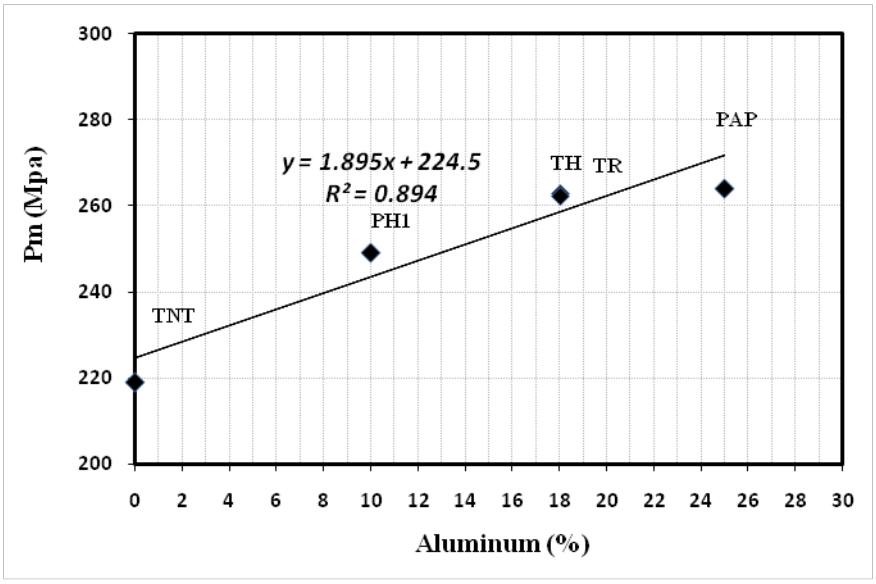

Figure 1. Peak pressure for tested explosive mixture.

3.2. Time constant for explosive mixtures

Time constants can be regarded as the time taken for peak pressure P(m) to decay to a value equal to P(m)/e. These values represent the major duration time of damage for underwater shock wave. Figure (2) shows that the time constants increase as the aluminum percentages increase which indicate that the high shock pressure will persist for longer time. This cause more damage to the exposed target.

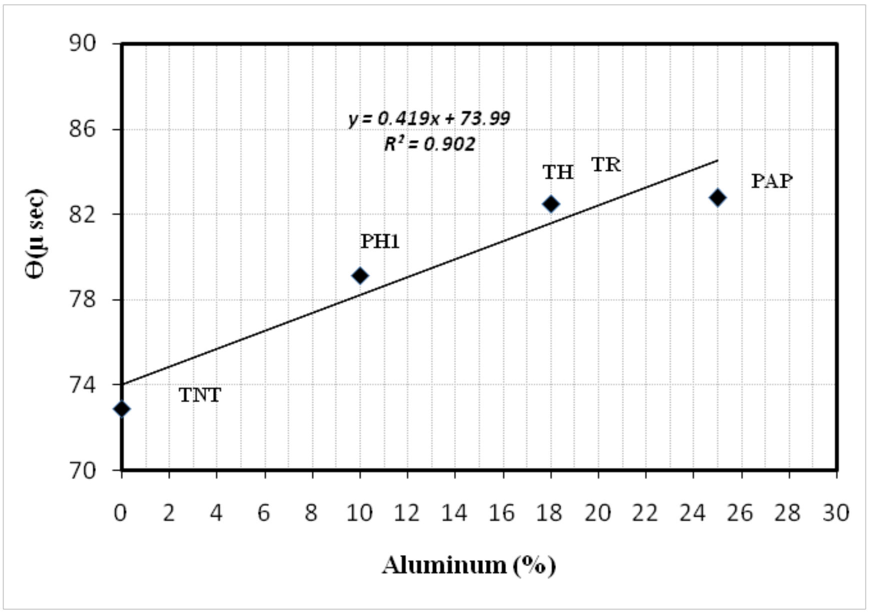

Figure 2. Time constant Θ for tested explosive mixtures.

3.3. Shock wave Energy for explosive mixtures

Shock wave energy (Esw) which represents the total shock energy produced by underwater explosion increases as the weight percentage of aluminum percentage increases as shown in figure (3). Higher percentage of aluminum increases the energy content of the explosive mixtures which make the heat loses during propagation of the shock wave lower than in case of using lower percentage aluminum mixtures.

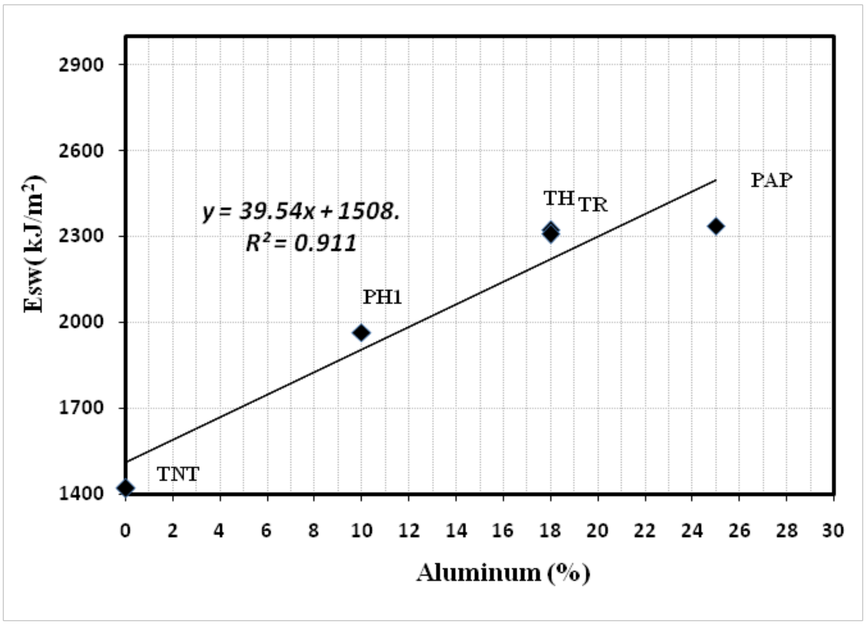

Figure 3. Shock wave energy for tested explosive mixtures.

3.4. Maximum bubble radius for explosive mixtures

It was observed that the maximum bubble radius, produced by 1 kg of the tested explosive mixture, increases as the weight percentage of aluminum increases. This due to the aluminum effect on increasing the energy and the gaseous detonation product for tested explosives. Figure (4) shows increasing on the maximum radius of the gas bubble as the aluminum percentage increases.

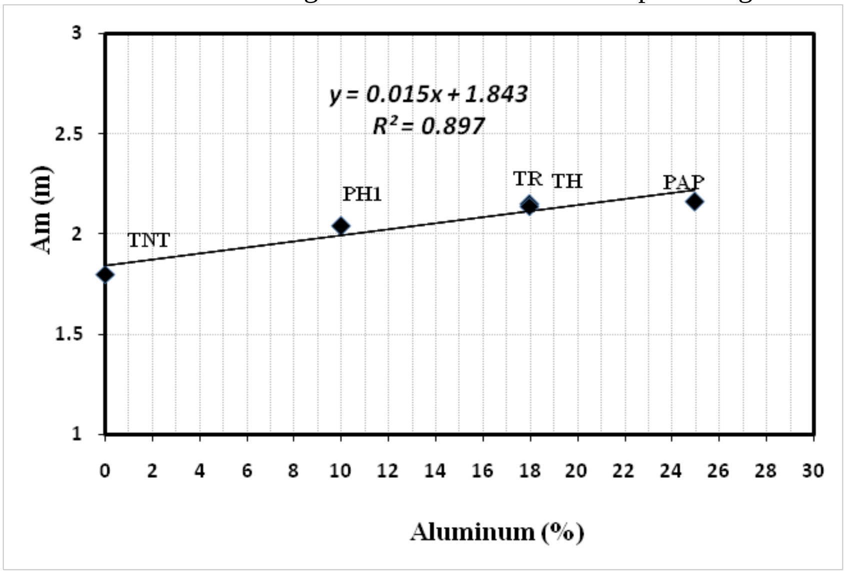

Figure 4. Maximum radius for tested explosive mixtures.

3.5. Bubble period for explosive mixtures

The first bubble period which is the duration between the first pulse generated by shock wave and the second pulse generated by the first bubble expansion for the all tested explosives mixtures are shown in figure (5).The bubble period increases as the aluminum percentage increase which made the damage resulted from the expansion of the gas bubble is greater than the lower aluminum percentage compositions.

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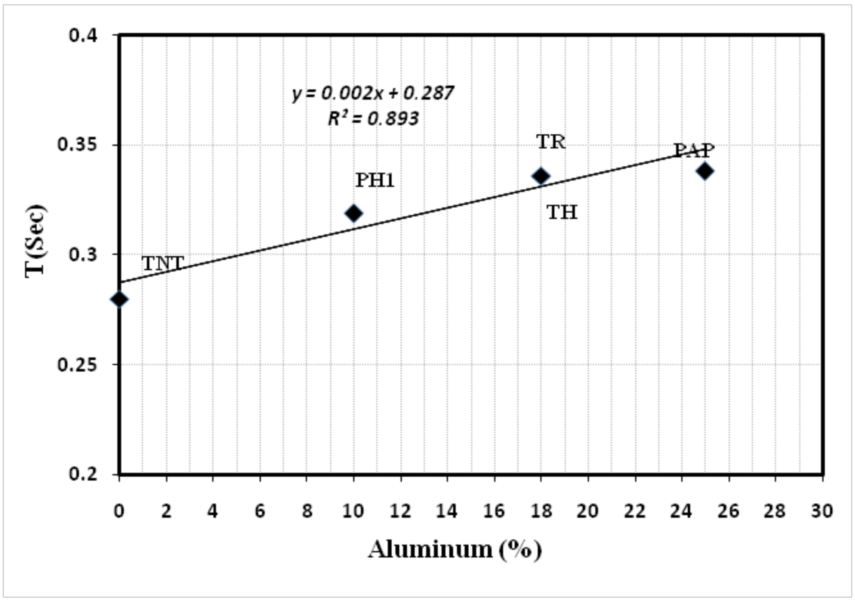

Figure 5. Bubble period for tested explosive mixtures.

3.6. Shock factors for explosive mixtures

Figure (6) represents the shock factors resulting from the underwater explosions for all tested explosive mixtures according to equation (4). Shock factors are increases as the weight percentage of Al increases. All results indicating that the target exposed to the lethal damage. The shock factors depend mainly on the weight equivalent of TNT of the explosive mixtures which mainly depends on the heat of explosion for the explosives mixture. The results obtained showed that the main effect of aluminum is increasing the energy of the explosives mixtures which give more underwater damage ability to the attacked target.

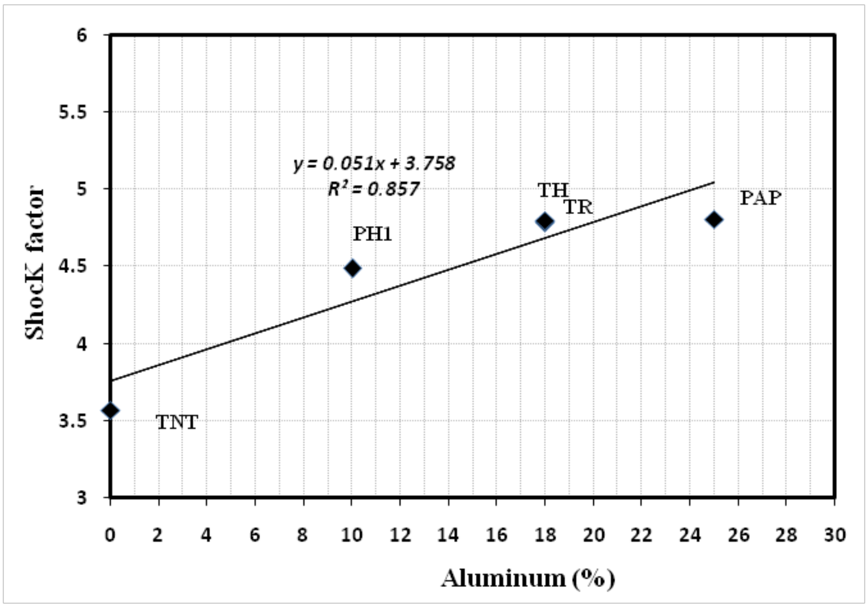

Figure 6. Shock factor for tested explosive mixtures.

4. Preparation of the explosive mixtures

Thermo-chemical calculations showed that many explosive formulation as TNT PH1,TH,TR, and PAP should be chosen for investigation the influence of the percentage of aluminum on the explosive mixture. Besides the high performance of that selected compositions, it provide more variety for comparisons with different performance parameter. All compositions are compared with TNT as a reference charge for choosing the most promising mixture suitable for free field underwater explosion experiments. Two preparation process which represent the casted explosives and the PBX explosives have been used for filling the explosive charge container.

4.1. Materials

The specifications of the used chemicals in this research including function, density and its source are listed in table (3).Also the mechanical and physical properties for the used steel 37 are listed in table (4).

Table (3) Materials used in the study

Material	Function	Density (g/cm^3)	Source	Notes
Aluminum	Reactive metal	2.70	Western Germany	<40 μm
RDX	High explosive filler	1.8	Heliopolis company , Egypt	Waxed
HMX	High explosive filler	1.9	Eurenco, France	Waxed
TNT	High explosive filler	1.6	Heliopolis company , Egypt	--
HTPB	A hydroxy terminated prepolymer	0.90	3N company ,USA	mg eqv. OH/g HTPB = 0.8465
DOZ	Plasticizer	0.91	3N company ,USA	--
HMDI	Curing agent	1.06	Aldrich, Germany	mg eqv. NCO / g HMDI = 11.8
Ammonium perchlorate	oxidizer	1.95	3N company ,USA	<200 μm

Table (4) Steel 37 properties

Properties	Yield stress (MPa)	Ultimate stress (MPa)	Elongation (%)	Rupture strain(%)	Density (kg/m^3)
Steel 37	290	330	33	39	7890

4.2. Preparation of melt cast explosive mixtures

Compositions of melt cast explosives based on RDX, HMX, TNT and Al were prepared according to the following procedure

- The TNT was placed into metallic container and heated at 90 °C for approximately 30 minutes until complete melting.
- After the melting of TNT, Al and RDX, HMX were added slowly on stirring to the melting TNT.

- Stirring was continued for approximately 30 minutes after the complete addition of aluminum to get a good mixing.
- After the good mixing of melted explosives, the mixture was poured in the molten state into a suitable container where it solidified immediately.
- Booster composed of waxed RDX weighed 20 g is placed into the explosives to complete the explosion train.
- The prepared mixture was cooled in open airfor complete solidification, then weighed and reported.

4.3. Preparation of PBX explosive mixtures

Compositions of PBXs based on RDX, HMX, AP, Al and polyurethane binder system (based on HTPB) were prepared according to the following procedure:

- Binder matrix including HTPB, HMDI and DOZ placed in a mixing kettle, in a water path
- Explosives and Al was then added in small portions during mixing for 1/2 hour.
- The formed matrix (paste) was then poured in the molten state into a suitable container.
- The prepared compositions were left for curing.

4.4. Design of underwater explosive charge

The general shape of underwater explosive charge container is shown in figure (7). The container made from PVC tube closed from the top and bottom with aluminum ring. Containers were filled with 5 different explosive mixtures which had been selected and prepared according to its theoretical underwater explosion parameter. The non-electronic detonator was fixed on the top ring to start the explosion train and transfer the detonation wave to the booster.

Figure 7. Photos of explosive charges.

5. Measurements of the underwater explosives performance

Underwater explosion test are completely different than any explosion occurred in air, as it contain the effect of both bubble and shockwave on the attacked target. The main parameter which was experimentally determined was the plate deformation caused by underwater explosion which can be used for calculation of the impulse of the tested underwater explosives.

5.1. Experimental setup for underwater study

Commercial mild steel sheets of 800×800×8 mm were placed on a container, made of polypropylene, and subjected to underwater explosion. The charge was suspended in the sea water at distance 300 mm from the surface of the steel sheet and was initiated by non-electric detonator as shown in Fig. 8. Safety fuse was used for initiation of the detonator.

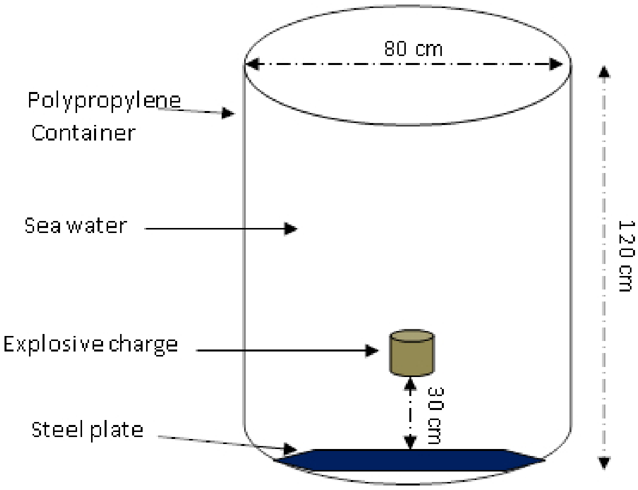

Figure 8a. the setup of the underwater explosion test

Figure 8b. Photos of the experimental setup

5.2. Plates deformation measurements

Shortly after the explosion, spray domes are observed and visual examination for the examined plate has been carried out. Clear deflection according to the resulted shock wave from underwater explosion has been measured. This deflection is showing in figure (9). The variation of central deflection for all different compositions with respect to TNT has been measured experimentally.

Figure 9. Plate deformation caused by underwater explosions

Figure (10) represent the effect of increasing the aluminum percentage of different explosive mixture with the resulted central deflection. The figure shows that the increasing of the aluminum percentage on explosive formulation will increase the deflection on the steel plate which means that more damage to the target. PAP mixture which represents the more energetic mixture according to its theoretical calculation will produce more deflection and more damage to the exposed plate which make the PAP mixture which contain lower percentage of explosives is more recommended for naval application.

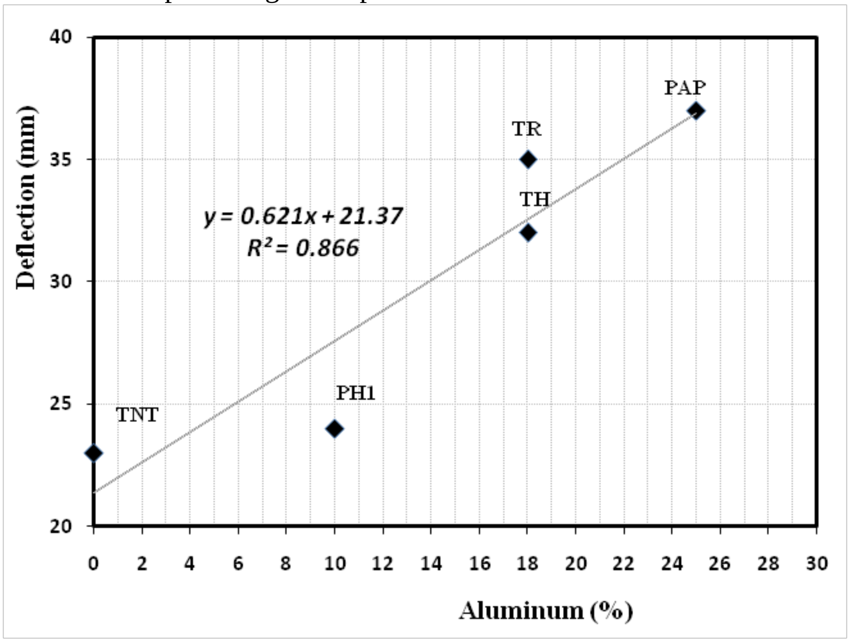

Figure 10. Effect of aluminum percentage on the central deflection for different explosives mixtures.

Plotting the impulse with the measured deflection in figure (11) will represented by straight line relationship which means that the impulse will proportional with the deflection and this a good agreement with theoretical result.

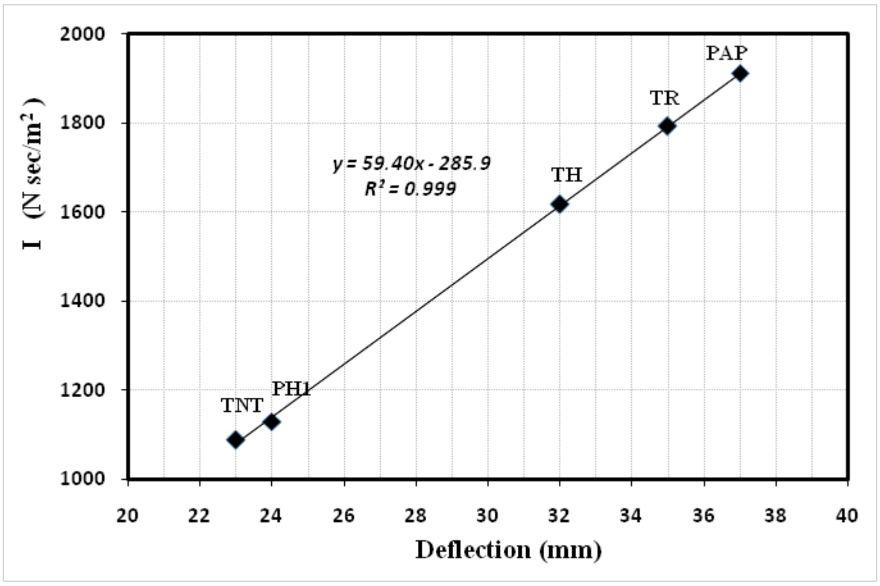

Figure 11. Relation between central deflection and the impulse for different explosives mixtures

6. Conclusion

Application of explosion heat which resulted from EXPLO 5 code for estimation the underwater explosion performance will help in choosing the explosive compositions which candidate for suitable naval application. Deformation evaluation of 6 mm steel 37 subjected to underwater explosions have been shown that the increasing of aluminum percentage on the explosive formulations will increases the damage ability for this explosive mixture. Anew relations between aluminum percentage of the explosive mixture and the measured deflection have verified the great effect of aluminum percentage till 25%. PAP compositions which produce more underwater explosion performance than other explosive mixture will be candidate for using in naval application.

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