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Shock Wave Behaviour of Polymeric Materials for Detonation Waveshapers

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ABSTRACT

This paper discusses the experimental determination of explosive shock attenuation parameters of four different polymers viz., Teflon, Phenol formaldehyde, Polyethylene foam and Polypropylene foam. These polymers are candidate materials for waveshapers in shaped charge warheads. Cylindrical specimens of the polymer materials were subjected to explosive shock loading by the detonation of RDX:Wax (95:5). Shock arrival time was measured using piezo-wafers positioned at known spatial intervals in the specimens. Initial shock velocity, stabilised shock velocity and attenuation constant were determined. These parameters are essential for the design of waveshapers. Foams have better shock attenuating properties compared to solids due to their cellular structure. Polypropylene foam has the highest shock attenuating characteristic among the four materials studied.

Keywords: Shock wave attenuation; Polymeric material; Waveshaper

1. INTRODUCTION

Many anti-tank weapon systems employ shaped charge warheads that are initiated peripherally using a waveshaper. Waveshapers are used in shaped charges to convert point initiation into peripheral initiation resulting in higher jet tip velocity with a lesser length of explosive charge. The design of a waveshaper is carried out such that the shock wave through the waveshaper material always lags behind the detonation wavefront. This criterion ensures that the detonation front always interacts with the shaped charge liner surface first rather than the shock travelled through the waveshaper material. A detonation wave that impacts in a more acute angle drives the liner material to higher velocities in a shorter time than this could be achieved with a side-on detonation wave[1]. A properly designed waveshaper transfers maximum explosive energy onto the metallic liner and thus accelerating it to hyper velocities.

Lightweight and good shock attenuation properties are important characteristics of waveshaper materials. Hence, polymer materials are very much suitable for waveshapers. It is essential to know the shock attenuation parameters of the material for designing a waveshaper. The attenuation of shock waves from contact detonation of explosives on polymer materials is not reported widely.

When an explosive is detonated in intimate contact with the material, the tremendous force of the explosion induces stresses within the material. These induced pressures are often short-lived as against the sustained pressure during static loading. The magnitude of pressures these materials are subjected to by explosion products is at least an order higher in magnitude than what is encountered in static loading conditions[2]. The high transient pressure generated by detonation moves through the material as transient stress waves. The strength of the stress pulse gradually attenuates due to energy loss within the material. The shock wave turns into a stabilised elastic wave after travelling a certain distance through the material. The structure of the material plays an important role in determining the attenuation characteristics of the material. Yadav[3] studied analytically the attenuation of the one-dimensional non-uniform shock wave produced by the impact of a flyer plate on a solid target. Attenuation of the shock wave takes place when it starts interacting with the head of the rarefaction wave. Erkman[4], *et al.,* studied the problem of the attenuation of the shock wave produced by the collision of Aluminium flier plate on Aluminium and Teflon target materials. He observed that the fluid model for treating the shock wave travel in metals was not well suited for Teflon. Xu[5], *et al.* studied the attenuation characteristics of Aluminium foam sandwich panels subjected to blast loading. He observed that the structural form of the material and the interface effect were important factors for the attenuation of shock in the material. Boey[6] has presented similar findings through ballistic trials that the porous structure of the material is an effective shock attenuator. Harvey[7] studied the attenuation of shock waves in Copper and Stainless steel targets by conducting flyer plate impact experiments. He observed the attenuation of the shock wave by the following release wave.

Polymer materials are very complex in nature and usually tailor-made to achieve desired properties. The cellular structure of foam materials has a high shock-absorbing capability. Closed-cell foams have better shock attenuation characteristics as compared to open-cell foams. In closed-cell foams, energy absorption is primarily due to the compression of trapped air and in open-cell structure by the absorption of the energy by

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deforming and causing airflow in the cell matrix[8]. Material properties and constants are not readily available for the choice of materials one wants to use. Hence, design and performance analysis of components like waveshapers using theoretical methods is difficult in the absence of such properties. Therefore, it is essential to determine such parameters experimentally.

Interaction of detonation wave with an inert material is described by shock hugoniot of the material. The properties of the shock generated in the material are determined by the impedances of the detonation products and the material. When a shock passes from low to high impedance across the material interface, shock pressure increases and vice versa[9]. The impedance of polymers is generally lesser than that of the detonation products. This results in the generation of shock pressure at the interface lesser than the detonation pressure. Hence, polymers are well suited for detonation waveshapers.

The experimental work presented in this paper describes the determination of shock attenuation parameters of four different polymeric materials viz., polyethylene foam, polypropylene foam, Teflon and phenol-formaldehyde. Two of the materials selected are foams and the other two are solids. Warheads are prepared either by explosive powder compaction or explosive melt casting. Waveshapers are embedded in the explosive material of the warhead. Waveshapers can be embedded in the explosive in-situ during the explosive powder compaction process under high-pressure loads. In this case, solid materials are preferred for waveshapers to maintain structural and dimensional integrity and also for proper load transfer during explosive powder compaction. In the case of the melt cast process, the waveshaper is placed in a cavity made by machining the cast explosive pellet. Waveshapers made of foam materials are suitable in this case to get filled inside the premade cavity without leaving any gap between explosive and waveshaper.

2. SHOCKWAVE ATTENUATION IN WAVESHAPER MATERIAL

The design of the waveshaper is based on the limiting value of shock travel time in waveshaper material and detonation wave travel in the explosive[10]. A good design of waveshaper and proper selection of material result in low warhead weight, less warhead space, maximised explosive content, increased target penetration and repeatability of performance.

Shock velocity attenuates exponentially as it travels through the material as shown in Fig. 1. The mathematical treatment and the attenuation parameters are given in the following paragraphs.

A point (X_0, Y_0) on the waveshaper surface is determined by equating the time taken for the detonation wave to reach that point around waveshaper (i.e. $T_1 + T_2$) and the time taken by the shock wave to reach the same point through the waveshaper (i.e. $t_1 + t_2$) as shown in Fig. 2[11].

$$T_1 + T_2 = t_1 + t_2 \tag{1}$$

The time taken for the shock wave to reach location (X_0, Y_0) through the waveshaper material, i.e. t_2 is dependent on the shock behaviour of the material. An exponential form of the equation is generally used for representing the shock velocity in

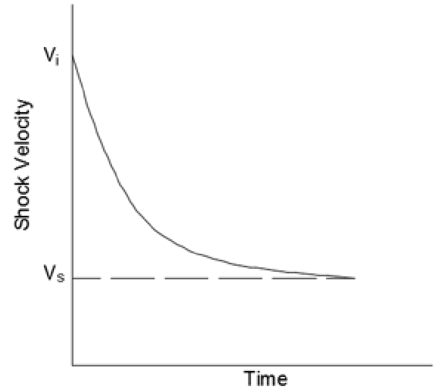


Figure 1. Exponential decay of shock velocity.

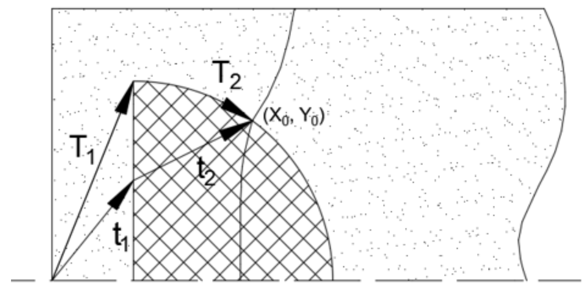


Figure 2. Detonation and shock travel in waveshaper.

the material. V_i and V_s are initial and stabilised shock velocities in the material respectively and γ is the attenuation constant. The shock velocity at any time *t* and distance travelled by this shock in time *t* can be written as

$$V(t) = (V_i - V_s)e^{-\gamma t} + V_s \tag{2}$$

$$X(t) = \frac{(V_i - V_s)}{\gamma}\left(1 - e^{-\gamma t}\right) + V_s t \tag{3}$$

The profile of waveshaper is dependent on *X* and can be estimated if V_i, V_s and γ of any material are known. Stabilised shock velocity (V_s) in the material is representing the bulk sound velocity of the selected material. The initial shock velocity (V_s) and attenuation constant (γ) are dependent on the quantity of explosive used for contact detonation[12]. Minimum dimensions of waveshaper can be calculated using the Eqn (1) if these values corresponding to the same explosive loading conditions as that in the warhead configuration are known. Experimental determination of V_i, V_s and γ for the four polymer materials considered are explained in this paper.

3. MATERIALS AND METHODS

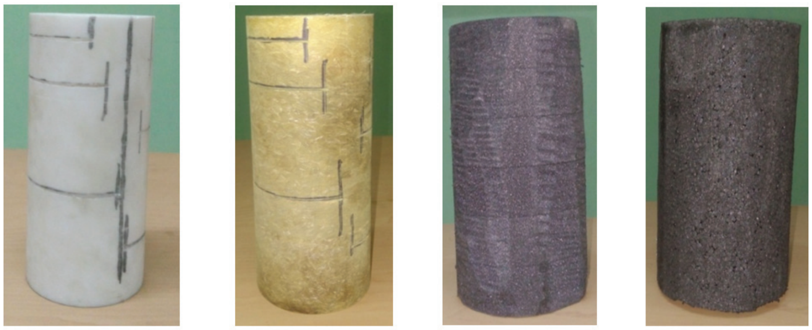
3.1 Materials and Sample Preparation

Experiments were carried out to determine the shock attenuation parameters for four polymeric materials viz., Teflon, Phenol formaldehyde, Polyethylene foam and Polypropylene foam. These materials were considered for the present study owing to their favourable properties for waveshapers. They are lightweight, thermally and dimensionally stable and easily manufactured into different shapes. These materials were conforming to the specifications given in Table 1.

Cylindrical test samples of diameter 90 mm and length 200 mm as shown in Fig. 3 were prepared from each material.

Table 1. Material specifications and properties

Material	Specification	Density (g/cc)	Tensile strength (MPa)
Teflon	IS:14635: 1999[13]	2.14	24
Phenol formaldehyde	IND-ME-951 Grade A[14]	1.80	80
Polyethylene foam	IND-ME-1022 Type 2[15]	0.045	0.5
Polypropylene foam	ARPRO™ from JSP[16]	0.06	0.8



(a) (b) (c) (d)

Figure 3. Test specimens: (a) Teflon (b) Phenol formaldehyde (c) Polyethylene foam (d) Polypropylene foam.

Teflon rods were machined accurately using a single point tool on a lathe machine to achieve the desired dimensions. Rods of Phenol formaldehyde were made using a moulding process under elevated temperature and pressure. It consisted of Phenol formaldehyde as resin and glass fibres as fillers. After the moulding process, final dimensions were achieved by machining the specimens on a lathe machine using single-point tool. Polyethylene foam specimens are cross-linked, closed-cell foam made using the Nitrogen gas foaming process. Blocks of foam materials were made into cylindrical specimens by high-speed turning operation. Polypropylene specimens were made by fusing polypropylene beads using a process called steam chest moulding[17]. Cylindrical moulded pieces were turned to achieve the final dimensions using a single point tool. After the cylindrical specimens were made, slots of width 1 mm were cut at distances of 15 mm, 30 mm, 45 mm, 80 mm, 120 mm and 160 mm from the surface of the test piece where explosive detonation was initiated.

Sensor locations are shown in Fig. 4. Piezo-electric sensors of square wafer configuration having a thickness of 300 µm were inserted in these slots to capture the arrival time of shock waves at these locations. Plastic shims of suitable sizes were used to fill the gaps and to ensure the sensor surface is in contact with the specimen. The depths of the slots have been varied in such a way that the arrival of shock waves at different sensing locations is not affected by the presence of slots above. Electric charges are induced due to the mechanical stress experienced by the sensor when the shock wave interacts with the sensor. Thus the shock arrival time at different sensor locations is determined.

Ceramic wafers made of piezoelectric material $PbSr_{0.025}La_{0.025}(Zr_{0.54}Ti_{0.46})O_3$ have been used to sense the shock arrival, Fig. 5. These wafers are made using tape casting process [18] and they exhibit a high piezoelectric voltage coefficient in the range of 300-325pC/N. This characteristic makes them suitable for sensor applications where high voltage sensitivity is in demand[19].

A circular disc of RDX/Wax (95/5) having a diameter of 90 mm and thickness of 10 mm was placed in contact with the test specimens to shock the materials under investigation. Explosive discs were prepared by pressing and compacting explosive powder to a density of 1.63g/cc. The detonation velocity of the explosive is 8470 m/s at the above density.

3.2 Experiments

Two experiments were carried out with each material as per the layout shown in Fig. 6. An explosive disc was detonated in contact with the material specimen using an electric detonator. A machined cover plate made of Aluminium was used to hold the explosive disc and detonator. This arrangement ensured the axisymmetry of the initiation of explosive within a tolerance of 0.1 mm. As the shock wave impinges on the piezo sensors embedded at known locations, an electric charge is generated which are monitored through a digital

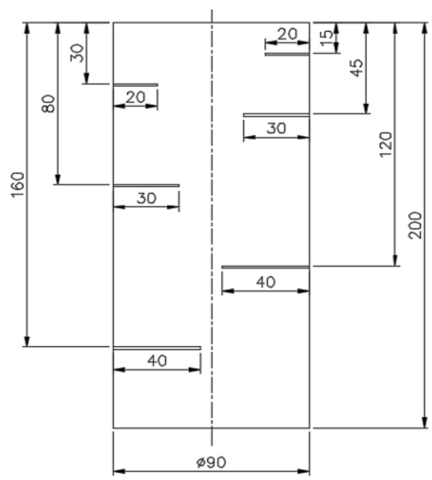


Figure 4. Sensor locations.

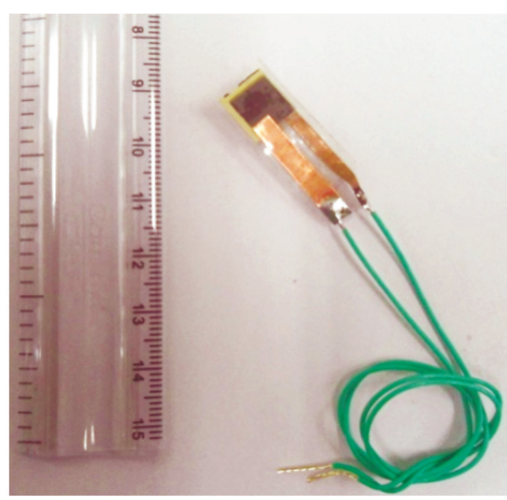


Figure 5. Piezoelectric wafer.

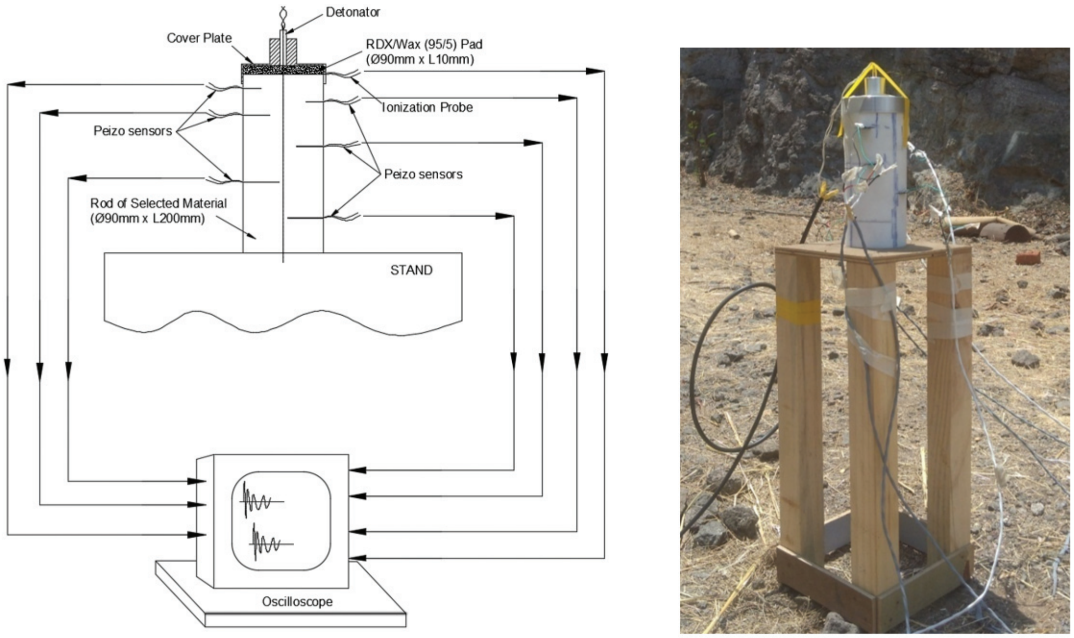


Figure 6. Experimental set-up.

oscilloscope. Shock arrival time at different locations was thus measured. The start time for the event was the detonation of the explosive disc. This was measured using an ionisation pin embedded inside the explosive.

3.3 Results and Discussions

Measured shock arrival time in each experiment shows that the results are consistent within a maximum variation of 10%. This variation is considered acceptable for the application we have considered since an additional margin of 10% thickness is generally provided on the waveshapers designed using the measured values.

The average value of the shock arrival time has been obtained from the two experiments conducted for each material. Method of non-linear least squares has been used to fit the curve to Eqn (3). This equation has been arrived at by integrating Eqn (2) which is the exponential form for shock velocity. Shock wave attenuates exponentially to a stabilised velocity which is represented by the bulk sound velocity of the material.

To fit the data in the given form, the value of stabilised velocity was experimentally determined. Ultrasonic waves of known frequency were passed through the samples of the material. Sound wave velocities were determined for the four different materials under consideration using the through-transmission technique. The values of bulk sound velocities so obtained are given in Table 2.

Table 2. Bulk sound velocity of the selected materials

Material	Density (g/cc)	Bulk sound velocity m/s)
Teflon	2.14	1200
Phenol Formaldehyde	1.75	2400
Polyethylene Foam	0.045	250
Polypropylene Foam	0.06	800

Polyethylene foam has the lowest bulk sound velocity and Phenol-formaldehyde has the highest. The value of bulk sound velocity depends on the bulk modulus and density of the material. The structure of the material plays an important role in determining the bulk sound velocity. In general, polymer foams have a lower bulk sound velocity as compared to solid materials.

Using the values of bulk sound velocities for the materials considered, average values of arrival time has been fitted to an exponential form. Values of constants, V_i, V_s and γ for the least square fit are given in Table 3. The Sum of squares of the error values was minimised by varying V_i and γ while V_s was kept constant at the experimentally obtained value of bulk sound velocity to arrive at the exponential fit.

Table 3. Constants for shock equations

Material	V_i (km/s)	V_s (km/s)	γ
Teflon	3.070	1.20	0.0160
Phenol-Formaldehyde	3.634	2.40	0.0181
Polyethylene foam	2.907	0.25	0.0087
Polypropylene foam	2.953	0.80	0.0181

Figure 7 shows that the shockwave arrival time at various stations where the sensors were mounted follows a non-linear trend. This trend was captured very well through an exponential fit of an equation as given in Eqn. (3). In Fig. 7, arrival time values recorded for the two identical experiments are shown in each subfigure. The results of the two experiments are quite consistent. Hence, it is possible to average the two values. Accordingly, the exponential curve is fitted using the average values. Shock velocity plot along the length of each material is plotted in Fig. 8 using the constants given in Table 3.

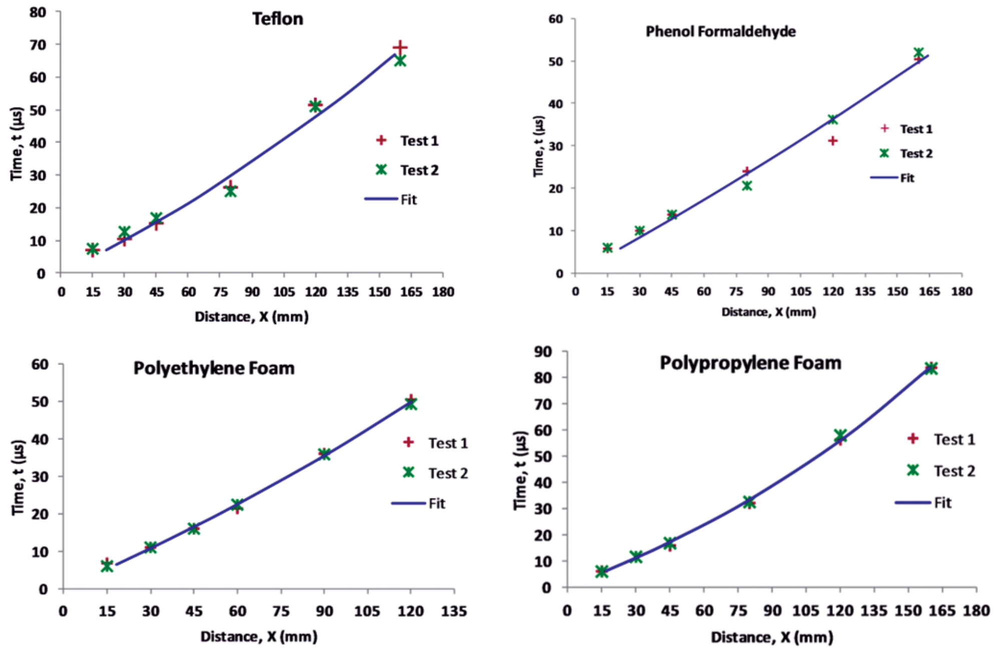


Figure 7. Shock wave arrival time in polymeric materials.

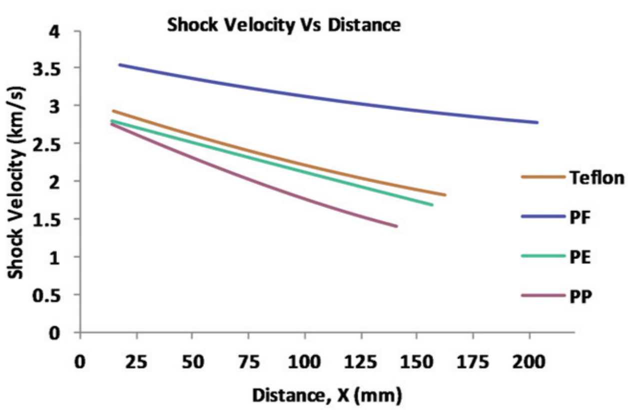


Figure 8. Shock velocity along the material specimens.

V_i and V_s represent the initial and stabilised shock velocities. However, it is to be noted that V_i represents the intercept on the y axis for the plot of a particular experiment conducted. Interface shock wave velocities calculated using hugoniot of the explosive-inert material system will be higher than what is obtained from these curves. This is due to the explosive thickness effect as observed by Held[20]. In the experiments conducted with different thicknesses of the explosive column, he observed that beyond a thickness of 50 mm, shock wave arrival time is constant in plexiglass up to a distance of 20 mm. Below 50 mm thickness of explosive, a lower shock velocity is recorded at the interface. He also observed that if the explosive thickness is close to 100 mm, the shock wave velocity in the first 20 mm of plexiglass corresponds to the CJ pressure. Hence, it is relevant to mention that whenever shock characteristics are determined for the design of waveshapers, it is necessary to incorporate all the explosive elements like a booster, precision initiation coupler etc. as provided in the warhead along with the explosive column above the inert material. Since the shock characteristics are dependent on the input pressure, the type of explosive used to shock the material is important for the estimation of the constants. In the present study, RDX: Wax 95:5 has been used to obtain the characteristic curves. The same curves will not be applicable for any other different explosive. However, the curves are useful for trend analysis.

It is seen from the above curves that the shock velocity attenuates as it travels through the specimen. The exponential equation as given in Eqn (2) is fitted to represent the behaviour. Shock attenuation characteristics of materials depend on the structure of bulk. Polymers have better attenuation characteristics than metals and in particular polymer, foams are porous and hence, attenuate shock more. The four polymer structures studied can be categorised into two classes. Polyethylene and Polypropylene are expanded foams and Teflon and phenol formaldehyde are hard plastics. It is seen that foams have better attenuation characteristics as compared to hard plastics due to their material structure.

Polypropylene foam has the highest attenuation of shock waves among the materials studied. Expanded polypropylene foam has a closed-cell structure having high energy absorbing capacity and is lightweight. The test unit was made by fusing beads of polymer using the steam-chest moulding process. It can also be seen from Table 3 that the four different materials have different initial shock velocities when they are subjected to the same explosive loading. As explained in Section 1, the shock pressure generated at the interface of the material depends on the impedance of the material. The lower the impedance of the material, the lower the shock pressure at the interface and hence, low initial shock velocity. Hence, polyethylene foam has the lowest initial shock velocity.

It is also interesting to note that polypropylene and phenol formaldehyde have the highest shock attenuating constants. However, polypropylene has lower shock velocity with distance. This is because phenol formaldehyde has a higher initial shock velocity and stabilised shock velocity owing to higher impedance compared to polypropylene.

Though all the materials considered in this study are suitable for waveshapers, Polypropylene with high attenuation and low impedance is the best choice. However, hard plastics like Teflon and phenol formaldehyde are particularly useful for incorporating in warheads where press filling of explosive is adopted.

4. CONCLUSIONS

Shock attenuation characteristics of four different polymeric materials namely, Teflon, Polypropylene foam, Polyethylene foam and Phenol formaldehyde have been investigated experimentally. Piezoelectric wafers with very high piezoelectric coefficients were used to record shock arrival time at known distances. Shock attenuation in the material is exponential and the constants have been determined experimentally and are given in Table 3.

From this study the following conclusions can be drawn:

(i) All the materials considered for the study are candidates for waveshapers in shaped charges.

(ii) Shock wave velocity in these materials has been determined by plotting the time-distance curve for each material. Initial shock velocity and attenuation constants for each material were determined from the exponential equation for the shock wave.

iii) Bulk sound velocity of materials were obtained using ultrasonic through-transmission technique and these values were used in the exponential fit of shock wave time-distance plot.

(iv) Expanded polypropylene foam and phenol formaldehyde have the highest shock attenuation constants among the four materials studied. Polyethylene foam, phenol formaldehyde and Teflon have the attenuation characteristic in the reducing order.

(v) Lower impedance of polypropylene foam coupled with its higher attenuation property makes it the best choice f or waveshaper out of the four materials studied.

(vi) Shock wave attenuates to an elastic wave after travelling through the material and expanded polypropylene foam attenuates the shock faster. Hence, a lower thickness of waveshaper can be designed out of this material. This material can be used in applications where impact shock absorption is required.

(vii) This study incorporates a specific explosive to determine the attenuation characteristics of materials under consideration. However, the attenuation trend displayed by these materials will be the same irrespective of the type of explosives.

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