Rigid polyurethane foam as an efficient material for shock wave attenuation

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Abstract. A new method for reducing parameters of blast waves generated by explosions of HE charges on ground is presented. Most of the traditional techniques reduce the wave parameters at a certain distance from the charge, i.e. as a matter of fact the damping device interacts with a completely formed shock wave. The proposed approach is to use rigid polyurethane foam coating immediately the explosive charge. A distributed structure of such a foam block that provides most efficient shock wave attenuation is suggested. Results of experimental shock wave investigations recorded in tests in which HE charges have been exploded with damping devices and without it are compared.

1. Introduction

At present, the majority of available blast wave localizers use predominantly mechanical energy and momentum absorption and dissipation techniques based on multiple reflections of shock waves from an assembly of obstacles and on entrainment of condensed phase of a shield by the gas flow behind shock front. In particular, water-based or polymer foams of various density are used for the shock wave attenuation as described in [1, 2, 3, 9, 10].

There are two basic ways to use foam for explosion localization - coating the charge with a large amount of low density water-mechanical or polymer foam or shielding objects to be exposed to a shock wave with a layer of polymer foam. For example, in [2], blast effect of explosion of a 285 g TNT charge was significantly reduced with a cubic meter of water foam. The second approach assumes that the object exposed to blast wave must be known in advance. Therefore, this approach is not applicable to emergency explosion localization tasks (e.g., when surrogate explosive is to be destroyed). It is well known that the shock wave attenuation mechanism in polyurethane foams is similar to that in water-mechanical foams.

The main physical principle underlying functioning of all devices that damp blast waves is transfer of both energy and momentum from the gas flow to condensed phase of foams [3, 4, 5]. This process includes mechanical acceleration, heating, evaporation, and thermal decomposition of the condensed phase, which result in gas flow deceleration and cooling, i.e., in blast wave attenuation. In some situations, acceleration of the condensed phase can cause an opposite effect, namely, kinetic energy of...
the accelerated condensed phase is converted into pressure when it stops at a reflecting solid surface, increasing thereby the pressure behind the reflected wave to a level exceeding that inherent in the reflection wave in gas (with no foam) [5]. This mostly relates to foam shields adjacent to objects protected. The higher the shock wave amplitude the more prominent is the effect of accelerated condensed foam phase on the reflected shock wave amplitude. Weak shock waves behave as nearly acoustic waves when reflected from solid surfaces. Thus, factors that reduce the condensed phase acceleration would diminish the reflected wave amplitude. It would seem that shields adjacent to an object to be protected are inefficient. Inasmuch as the energy losses within the foam are quite significant the reflected wave pressure can nevertheless be lower than in gas with no foam shield under certain conditions. For example, destruction of thin partitions between cells in water foams, which increases gas permeability of foam, reduces the condensed phase acceleration but intensifies the energy exchange. This is true for polymer foams as well. On the other hand, entrainment of condensed phase by the gas flow attenuates the incident shock wave, therefore a layer of foam coating the charge would significantly reduce the amplitude of shock wave leaving the layer not only because of energy losses within the layer but due to difference in the acoustic impedances at the foam-air boundary. Explosion localizer efficiency depends on many factors, such as rigidity of foam, its density and structure, ability to resist intense (high speed and dense) gas flows, and thermal stability of the condensed phase. Unfortunately so far there is not too much information available in literature on how to select a proper material for foam, where it is to be disposed with respect to the charge and objects to be protected, and what foam density is needed to attain the most efficient suppression of the blast effect in each particular situation.

Porous structure of foams combines two important qualities, namely, gas permeability and high aerodynamic drag. Explosion products flow through it, allowing thereby them to expand, but at a low velocity, i.e., the amplitude of a shock wave entering the ambient air drops. This implies that to interact with the detonation products in the near zone around the charge the required density and rigidity of the foam material must be as close to those of the detonation products as possible. Low density water foams are least efficient in attenuation of shock waves in this zone. For the efficient energy exchange between the detonation products and foam material a sufficient quantity of the total mass of the rigid foam obstacle is also needed.

To solve the problem of the blast wave attenuation one should refer to polymer foams that have an elastic structure of sufficient rigidity. Authors of [6] studied attenuation of shock waves with triangular shaped pressure profiles by a cylindrical polyurethane foam block placed in a shock tube. It has been found that the shock wave amplitude behind the block diminishes when the block length is close to the incident wave pulse length. It is concluded also in [6] that as the foam mass and the amplitude of the wave increase so does the efficiency of the wave attenuation. Application of polyurethane foam to reduce the intensity of shock waves has been increasingly discussed in the literature in recent years [9, 10].

As shown in [9] the highest efficiency of attenuation is observed in a shock tube when the foam as a whole moves with the wave. The degree of wave amplitude reduction varied from 85 to 95% when foam blocks moved freely whereas it dropped to 18 - 60% for fixed foam blocks. That means that a greater attenuation effect can be achieved by setting a foam block as a barrier between the charge and the object to be protected as close to the charge as possible rather than by protecting the object with a foam layer coating its surface. Of course this is true provided only a part of the block hits the object while its major part is dissipated in the flight to it. This conclusion is supported by the fact that in some cases the shock wave pressure rises when porous foam layer coats the object [11]. That the shock wave attenuation is the higher the greater the Mach number of incident wave is another observation reported in [5] which confirms findings of authors of [6]. This leads one to conclude that the closer the foam block is positioned to the charge the more efficient its damping action on the shock wave amplitude. The mechanism of energy absorption in the course of polyurethane compression is examined comprehensively in [10]. We allocate the findings most important for further consideration. The foam 0.409 kg/m$^3$ in density is destroyed completely being compressed at an initial velocity...
exceeding 141 m/s, its interaction with a shock wave is mainly controlled by foam material viscosity and heat conductivity.

As the compression velocity decreases to 43 m/s, the dissipative processes associated with the viscoplastic flow within the foam structure begin to dominate in absorption of the compression wave energy. This implies that an increase in the heat capacity of the material (including heat expenditure for evaporation) in the close vicinity of the charge, and, at the same time, in the density of the foam structure at greater distances would favor the absorption of the explosion energy. Therefore the best way to absorb explosion energy by rigid polyurethane foam is to coat a charge with layers of different grades of foam material with various mechanisms of energy absorption depending on the distance from the charge.

Polyurethane based foams are widespread; their properties (density and size of cells) vary in a wide range depending on polymerization regime. Polyurethane foam formation requires water as an agent reacting with the isocyanate group (one of the components a) and producing carbon dioxide that fills the foam cells. Normally, reactants of such foams in the initial state consist of a mixture of polyol and isocyanate [8 p. 81]. When the mixture is activated by water, an exothermic polymerization reaction attended by gas evolution starts. To accelerate this reaction it is sufficient to increase the temperature of the reactants, for example, spraying the foam producing reactants together with hot water. The rate of elastic foam formation has been verified experimentally.

The reagents were sprayed together with boiling water. As a result, a 50-liter hemispherical foam block was obtained. The amounts of reagents and water consumed were 5 liters and 8 liters respectively. Water in this case was in excess compared to its amount needed to polymerize the reactants. The excessive water was introduced intentionally into the foam block in order to fill the foam pores closest to the charge zone in order to rapidly reduce temperature of the detonation products. The resulting material resembles a heavily wetted sponge. The average density of the material is about 280 kg/m$^3$. In the central part of the foam block, the material density was higher - up to 500 kg/m$^3$.

Such density distribution in the foam block has been provided deliberately and would be discussed below. These experiments show that a material consisting of polyurethane foam and water can be prepared in sufficient quantities in a short period of time. The block formation time can be reduced introducing a polymerization catalyst in the mixture of reagents [8].

Below we discuss plausible approaches to optimizing localization of the blast effect. In the area around the charge, keeping in mind the fact that the flow of products in this zone is laminar, it is necessary to place a foam with coarse open pores and density as high as possible (up to the use of metal foams). Such a foam material would enhance instability of the expanding flow of detonation products that generate the shock. The jets induced by the instability perturbations intensify drastically the energy and momentum exchange between the localizer material and gas flow, the temperature of the products and shocked gas is decreased additionally due to thermal decomposition of the foam material.

The first zone of interaction, let's call it an "instability zone", should be of an order of magnitude of the charge size or slightly thicker. The “instability zone” should be followed by water-saturated foam of lower density. Jets of the hot products turbulized in the “instability zone” would penetrate into that foam layer and mix intensively with water reducing thereby the gas flow temperature. The kinetic energy of moving products would induce a viscoplastic flow in the foam structure in the course of its deformation, which would further reduce the gas flow temperature. In addition, a multiple reflections of the shock wave within the foam enhances the dissipation of the energy and momentum of the gas and its mixing with water present in pores. All the aforementioned interactions would reduce the driver ability of detonation products.

Thus, the major damping processes occur in this second zone. At the end of interaction of the products with foam material in this zone (we call it "attenuation zone"), the foam block fragmented into separate small pieces would produce secondary dangerous high speed fragments. To mitigate action of this factor, as well as to further reduce the shock wave energy one more zone of interaction is
needed, where the damping material should be a low-density fine-cell foam. Secondary fragments formed in the “attenuation zone” would get stuck in the outer layer of the light foam loosing their kinetic energy because of high aerodynamic drag.

2. Experiment

To estimate the efficiency of shock wave attenuation by the foam block, a comparative test was carried out. First, a 500-g cylindrical (L/D=2) charge of granulated TNT was exploded on a flat sandy area. In the second experiment, an identical charge was covered with a polyurethane foam block prepared from the AKVIDUR™ [7] foaming agent. The block was nearly semispherical and had a distributed structure - the inner 5-10 cm layer of coarse foam, a 25-cm middle foam layer with a cell size of about 6-10 mm containing some amount of water, and an 8-10-cm outer light foam layer (see. Fig. 1).

![Figure 1. Schematic of the foam block:
1 – tube for detonator wires; 2 – outer light foam layer; 3 – middle water-saturated layer; 4 – detonator cap, 5 – HE charge.](image)

![Figure 2. Comparison of pressure profiles recorded in a test with and without foam block.](image)

Geometrical dimensions of the block were selected keeping in mind that the greatest efficiency of the blast wave attenuation would be in the case when the foam layer is comparable with the shock wave pulse length (see above). A charge 100 mm in ID consisted of 430 g of granulated TNT and 50 g of ammonite 6JV, was installed into a recess precut in the foam block. A 12-g ammonite charge 20 mm in ID with a 8-g RDX cap was used as a booster to initiate the TNT charge. The charge unit together with the foam block was installed on a steel plate (see. Fig. 1).

As a result, the pressure traces at different distances from the charge were obtained. The resulting pressure-time histories of the processes studied are displayed in Fig. 2. The records demonstrate a significant reduction of the shock wave amplitude and duration caused by the foam block. TNT equivalency of the explosion in terms of pressure amplitude was calculated based on pressure records, using the Sadovsky formula modified for granulated TNT [12], and on the times of shock wave arrival at the sensors, according to the method described in [15]. The coefficient of ground explosion energy absorption was set at 0.7. The results are shown in Table 1. The two methods of TNT equivalency assessment yield similar results. Slightly greater TNT equivalency value at shorter distances from the charge in the test with no foam is due to the cylindrical, rather than semispherical shape of the charge. The behavior of recorded signals changes qualitatively in the test with foam. The TNT equivalency values assessed based on the pressure records is much lower in the vicinity of the foam block whereas its values calculated using measured arrival times behave oppositely. It is clear that shock wave is damped by the foam quite efficiently, which follows from the low TNT equivalency value at the
position of the first pressure gauge. The shock wave pulse duration at this distance is slightly increased. However the detonation products partially “locked” within the block accelerate the foam layers and increase the shock wave amplitude. At later stages, the foam block fragments move obviously at a velocity which is close to that of the gas, therefore the TNT equivalency remains constant. TNT equivalency as determined based on arrival times is controlled by the shape of the shock front, which is certainly oblique because the charge is cylindrical, break through of the gas at the foam-metal plate interface can not be excluded either. These factors are able to increase the velocity of the leading shock wave edge affecting only slightly the overpressure value. At larger distances, all the transient processes (including oblique shock wave and break through of the detonation products along the metal plate) fade out and the TNT equivalency values as determined by the two methods are identical and remain constant. It is clear that assessment of the blast effect in a zone close to the charge employing the Sadovsky formula and pressure amplitudes yields more correct results.

Table 1. Results of measurements of the shock wave parameters.

| Charge type | $R$, m | $T$, ms | $P$, bar | TNTp, kg | TNTt, kg |
|-------------|--------|---------|----------|----------|----------|
| NO FOAM     | 1.053  | 0.65    | 9.8      | 0.58     | 0.46     |
|             | 1.585  | 1.42    | 2.7      | 0.42     | 0.5      |
|             | 2.096  | 2.5     | 1.4      | 0.4      | 0.44     |
|             | 2.766  | 4.08    | 0.79     | 0.4      | 0.42     |
| FOAM        | 1.053  | 1.7     | 0.6      | 0.015    | 0.085    |
|             | 1.585  | 3.04    | 0.56     | 0.045    | 0.075    |
|             | 2.096  | 4.42    | 0.36     | 0.05     | 0.05     |
|             | 2.766  | 6.28    | 0.23     | 0.05     | 0.05     |

3. Discussion
To compare efficiency of explosion localizer based on rigid polyurethane foam with other types of explosion localization devices and methods we plotted the overpressure versus reduced distance ($R' = R/m^{1/3}$, $R$ – distance from the charge in meters, $m$ – charge energy expressed in kg of TNT) for various cases of the blast wave attenuation (see Fig. 3). Unfortunately the graph provides incomplete information about efficiency of localizers because it demonstrates only its ability to reduce the shock wave overpressure not related to the amount of damping material. It is noteworthy that all the methods of blast wave attenuation yield the curves that lie below the Sadovsky curve for TNT explosion with no damping devices within the entire range of reduced distances. First of all, two types of damping devices are to be distinguished. Damping devices of the first type, like water curtains, are inevitably arranged at some distance from a charge where the wave amplitude is fairly low. They reduce the wave amplitude by a factor of two and lower. The localizers surrounding charges are much more efficient, particularly at high wave amplitudes. Light water foams coating charges reduce the high wave amplitude quite efficiently; the overpressure drops steeply as the distance increases. However this is certainly true within the foam block, that is, to attenuate the shock wave to a harmless level one needs foam blocks of very large volumes. The shock wave that escapes the block would decay slower than the blast wave spreading in air with no foam, because the water mass accelerated by the shock wave in the block would support it as a piston. Plastic bags filled with water, sand, and CaCl that cover a charge reduce significantly the shock wave overpressure in the range of few bars at reduced radii not exceeding 0.5. Although no data on the behavior of blast waves beyond these distances are available the curves suggest that the “blankets” are much more efficient than water curtains. The common feature of the above discussed localizers is that they absorb the major fraction of the kinetic energy and momentum of gas mechanically and the contribution of heat transfer from the gas to the condensed phase is insignificant when the filling agent is powder. This contribution is appreciable when the “blanket” is filled with water because water is brought up by the shock wave into fine droplets that evaporate, therefore this localizer is the most efficient among the “blanket”-type ones.
Unfortunately there is no information about how the expanding dense mass of the “blankets” can affect the surrounding objects due to its kinetic energy and how its further motion can influence the blast wave parameters. The data for the stratified foam lie within the same group, although the damper mass-to-charge mass in this case is lower (see below). The data however show some promising trend, namely, the damper efficiency tends to be better compared to that for the “blanket” devices both at shorter (the curve is less steep) and longer (the curve is steeper) distances from the charge. A possible explanation of this trend is higher energy losses at high shock wave amplitudes and lighter fragments of the foam material less supporting the wave at longer distances.

The range of overpressures to which the shock wave is to be attenuated in practice is fairly wide. Depending on the situation their level is dictated by necessity of protecting surrounding equipment or buildings. But most frequently it should not exceed lethality or injury threshold for people or animals. In any case the blast wave overpressure should be below few tens of bars or even below 1 bar. It is well known that overpressure is not the only wave parameter that defines the damage and lethality thresholds the other important characteristic is wave impulse, therefore as far as the safety problems are concerned, these two parameters are to be considered together. Results of our experiment show that the foam block reduces significantly the wave impulse (determined as an integral of pressure with respect to time) as well, however by a factor of 2 or 1.5 less than it decreases the overpressure. As expected, acceleration of the condensed foam phase by the gas results in formation of a kind of a gas-permeable piston that partially supports the blast wave and makes it longer. Therefore the wave impulse drops with distance from the charge slower than does overpressure. The foam increased the duration of the positive pressure pulse phase by a factor of about nearby the chare and about 1.5 at longer distances.

The damper mass-to-charge mass ratio which is the most important characteristic that defines the damper efficiency, can conveniently be presented as suggested in [13] by the explosion damper parameter (the cubic root of this ratio). As Fig. 4 shows, the stratified polyurethane foam device proposed in this work is superior to all the localizers information about which we have been able to find in literature. They include also the data on shock wave attenuation with the aid of standard polymer foam blocks piled up around a charge (Fontan)[13].
4. Conclusion

As a summary we can state that an efficient method for localization of ground explosions in vicinity of a charge is proposed. The method is based on application of stratified polyurethane foam blocks with an optimized structure. A distinctive feature of the method is fast in situ fabrication of the block and mobility of the equipment, possibility of remote control of fabrication. The optimal mechanism of interaction between the damping material expanding detonation products is discussed. Based on this mechanism, a possible construction of the foam blocks with differentiated porosity, composition and strength is suggested. The block should consist of several layers of foam with different characteristics: the inner one must be mechanically strong foam with coarse open pores and of high density in order to induce highly perturbed flow of the detonation products. The middle layer, of lower density and saturated with water serves as the main energy and momentum absorbing (damping) foam block unit. The function of the outer layer, made of light fine-cell polymer foam, is to decelerate fragments of the inner layers and reduce their number. In the comparative test performed, the TNT equivalency of the explosion was reduced by the block by a factor of 5 to 10 depending on distance from the charge. The proposed explosion localization method is shown to be superior to the known damping techniques in virtually all parameters.

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