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Abstract --The results of a feasibility test using Rigid Polyurethane Foam (RPF) as an operational anti-personnel mine counter-mine technique are presented. RPF, at a given density and thickness, can withstand the explosive effects of anti-personnel blast mines and mitigate or neutralize the effects of surface laid anti-vehicular mines. A 12-inch thick, 4 pound per cubic foot foam block completely contained a 10-gram explosive charge of PETN while a 30-inch foam block with the same density contained a 30-gram charge. A 24-inch thick pad supported 50 passes of an M88A2 Recovery Vehicle, crushing the foam no more than 2-3 inches throughout the length of a 56 foot foam roadway. Underneath this roadway, simulated land mines set at 14 psi were not triggered by the passage of an M88A2 and a HMMWV. Our experiments indicate that RPF can provide additional traction in muddy conditions and set-off explosives connected to trip wires. The pressure and trafficability experiments were conducted jointly with Sandia National Laboratories and the Waterways Experiment Station, Vicksburg, MS in July-August 1997, and the explosive experiments were conducted by Sandia National Laboratories at the Energetic Materials Research and Testing Center (EMRTC), Socorro, NM in August and October 1997.

Introduction

Mines, both anti-tank and anti-personnel, have been combat multipliers in past and present battlefields. When properly employed, mines can drastically reduce a unit's ability to maneuver its forces and synchronize its efforts on the battlefield. Currently, our land forces have breach in-stride techniques and countermine systems that can reduce a 300-meter long obstacle within ten minutes, but these techniques and weapon systems are slowly becoming obsolete against the rapidly evolving mine technology and techniques. It has been argued that the United States has made very little countermine progress since World War II, instead, the focus has been on developing fuzing, lethality, and emplacement technologies [Ref. 1]. This study presents new results using Rigid Polyurethane Foam (RPF) to improve current breaching techniques. The scope of this study is centered on anti-personnel mines, however this report also includes results of experiments that can be extended to anti-tank mines.

The purpose of this study is to determine if rigid polyurethane foam can be used to either neutralize or efficiently attenuate the explosive effects of surface or subsurface laid anti-personnel mines [Ref. 2, 3]. It will also determine if the foam is a viable system for operational use on the modern day battlefield. Feasibility experiments in the areas of trafficability, traction effects, trip wire reduction, foam repair, and explosive cavity formations provide information [Ref. 9] to determine the foam's applicability in military operations. One possible application is to spray the foam on a minefield and allow a combat unit to continue through the obstacle field with speed and avoid losses to the covering enemy unit. Rigid Polyurethane Foam could also be used as a temporary walkway as part of humanitarian efforts to protect civilian populations from mines left behind after a conflict.

Rigid Polyurethane Foam

The RPF [Ref.4] chosen for these feasibility experiments, NCFI 811-91, is a two-part liquid which can expand up to 60 times its original volume. The amount of expansion will depend on the desired strength of the foam. Because of this considerable volume expansion, this foam can be transported in minimum bulk for possible military applications. The two chemicals are 1,1-Dichloro-1-flouroethane (CH_3CCl_2F or HCFC-141b) and Polymethylenepolyphenylisocyanate (Polymeric MDI). The first chemical is the Polyol resin and the second chemical is the isocyanate. The mix ratio of the chemicals by volume is one part resin to one part isocyanate. The mix ratio by weight is 100 parts resin to 106 parts isocyanate. It has a cream time of 55-65 seconds and a rise time of 3-4 minutes [Ref. 5, 6].

Polyurethanes are formed from the reaction of a polyol with an isocyanate [Ref. 7]. The polyol, which means multiple alcohols or multiple OH groups, reacts with isocyanate, which is the N-C-O combination of atoms. When these two monomers combine, a more stable molecular structure results from the molecular rearrangement.

RPF has been used in a variety of applications, such as in the automotive and building industries, but it has been primarily used for thermal insulation, specifically for frozen containers fitted for trains, trucks, aircraft, and ships. In the automotive industry, RPF is used to fill longitudinal runners, motors, and trunk hoods in order to provide additional stiffening. The building industry uses RPF to fill gaps between door casings and walls [Ref. 8].

- Dr. Ronald Woodfin of the Exploratory Sensors and Fusing Department of Sandia National Laboratories conducted extensive experiments on RPF from November 1995 through February 1996. His results are contained in SAND96-2841. This Phase I report focuses on the "development of a foam that can neutralize mines and barriers and allow the safe passage of amphibious landing craft and vehicles" [Ref. 9]. Phase I concentrated on the following areas:
- Laboratory characterization of foam properties
- Field experiments with prefabricated foam blocks in order to determine its capability to carry military traffic
- Flammability characteristics
- Response to bullet impact
- Toxicity
- Explosive cavity formation from surface and subsurface shots

Feasibility Experiments

The feasibility experiments were conducted at two locations. The initial experiments were conducted jointly with Sandia National Laboratories and the Waterways Experiment Station, Vicksburg, MS at Duckport, LA [Ref. 10] while the explosive tests were conducted by Sandia National Laboratories, Albuquerque, NM, at EMRTC, Socorro, NM.

Waterways conducted a Concept Evaluation Program in order to determine the trafficability of a foam roadway, the ability of the foam to distribute the load of a static and moving vehicle, the effects of laying foam on trip wires, and finally the effects on sub-surface laid mines. These experiments were conducted at Duckport, LA between 25 July - 07 August 1997.

The Sandia experiments concentrated on the explosive effects on Rigid Polyurethane Foam blocks [Ref. 11, 12, 13]. Failure criteria of the foam based on density, explosive charge, and foam thickness were explored. The final experiments were conducted to determine the possibility and efficiency of repairing damaged blocks.

Both experiments were part of an integrated plan with Sandia National Laboratory playing the lead role. Because these were operational feasibility tests, mixed English and metric units are reported.

Trafficability Tests

These experiments were conducted in order to investigate the foam's ability to carry military traffic. A tracked vehicle, M88A2 Hercules Tank Retriever, and a wheeled vehicle, M998 High Mobility Multi-purpose Wheeled Vehicle (HMMWV), were used for these tests. The M88A2 weighed 138,000 lb and was fitted with an M60 track which produced a contact pressure against the road bed of 17.4 psi. The HMMWV weighed 9,490 lb with a front tire pressure of 25 psi and a rear tire pressure of 35 psi. The contact pressures on the ground were 20 psi and 26 psi respectively [Ref 2].

Set-up: An RPF roadway with dimensions, 51' X 26' X 2' was constructed on a flat plastic clay soil surface. The foam dispensing machine was a Decker Industries commercial model applicable to the building industry. This machine can only dispense foam at a maximum rate of 90 lb/min, which is not quick enough to dispense large quantities of foam in the required time for an in-stride breach. In order to construct the 24-inch thick roadway, the foam had to be dispensed in approximately four layers with each layer no more than 6 inches thick. When the layers were poured larger than six inches thick, the internal temperature in the foam increased. This heat buildup caused the foam to split. (The choice of foam composition for this experiment was not optimized for land use, but was dictated by use for other applications under water.)

***Experiment*:** The M998 HMMWV and M88A2 Tank Retriever were driven over the 24- inch deep, 4 lb/ft^3 foam roadway for a total of 50 passes each. Indentation measurements of the foam were taken after each pass, which was one length of the roadway.

Results: After the first five passes, the HMMWV vehicle barely indented the foam. In some areas where the foam was slightly higher, small cracks developed. After 50 passes, the foam was indented no more than 1/4 inch. The M88A2's first pass created an indentation up to an inch in depth in some portions of foam. After the second pass, the M88A2 began to pack the foam underneath the tracks and the debris began to settle on top of the worn surface. After 50 passes, the M88A2 crushed the foam between 2-3 inches throughout the length of the roadway.

Conclusions: The minimal damage created by 50 passes of the M88A2 would suggest that the foam roadway will be able to carry the passage of at least an entire battalion before repairs would have to made on the foam.

Trip Wire Experiments

Set-up: Five trip wires were positioned on the northern end of the roadway. Three of the trip-wires were M-1, 7 lb pull devices while the remaining two were string tension potentiometers. Each wire was anchored on one end to a wooden stake while the other end was attached to a tripping mechanism set at 7 lb. The wires were approximately two inches above the ground.

Experiment: The foam was poured into the trip wire area with a west to east fill pattern. The goal was to achieve a total foam depth of 24 inches.

Results: The foam immediately encapsulated the trip wires and the expansion of the foam caused the wires to rise. All five trip wire devices were tripped by the expanding foam.

Conclusions: RPF provides an operational means of triggering trip wire triggered devices prior to the passage of foot and vehicular traffic.

Effects on Sub-surface laid Mines

Set-up: Eight M15 training mines and eight pressure cells were employed under the same roadway used for the trafficability tests. Four of the pressure cells were rated at 50 psi and used for the HMMWV lane while the remaining four cells were rated at 100 psi and used for the M88A2 lane. The mines were buried approximately 2 inches deep and were set to be tripped after experiencing a load of 14 psi. The pressure cells were buried approximately 3 inches in depth and placed adjacent to the M15 mines in order to provide the loading data for each pass of a vehicle.

Experiments: Load sensor data was taken for each of the 50 passes of the M88A2 and HMMWV.

Results: Without the use of the foam, the M88 was calculated to have a surface contact pressure of 17.4 psi while the HMMWV had a contact pressure of 20 psi for the front tires and 26 psi for the rear tires. The load sensors indicated an average load of 5.4 psi for the M88A2 and 0.34 psi for the HMMWV. The Phase I report by SNL calculated similar values, 5.0 psi for the M88A2 and 0.5 psi for the HMMWV [Ref. 11:p. 109]. None of the simulated mines were triggered by any of the 100 passes over the foam roadway.

Conclusions: RPF was able to neutralize the effects of subsurface laid M-15 training mines.

Explosive Effects on RPF

Set-up: A twelve-inch thick layer of fine sand was placed on top of solid ground. Sand was chosen in order to provide a level surface for the foam blocks. Sand bags were placed on top of the foam blocks to ensure that the foam remained on top of the sand during the explosion. The smaller foam blocks will tend to elevate, thus causing a considerable air gap during the propagation of the explosive shock. The explosive used for these experiments was PETN, pentaerythritol tetranitrate, which is commonly used in grenades, small caliber projectiles, and demolition devices [Ref. 3:p. 6.13]. PETN has a conversion factor of 1.45 when scaled to TNT, i.e. 10 g PETN has the explosive effect of 14.5 g TNT. A patty-shaped explosive was chosen over a spherical shape in order to closely replicate the explosive geometry in an anti-personnel mine.

A two-part polyurethane dispensing machine made by Decker Industries, Florida, was used to make the 15 foam blocks for this experiment. This was also the same machine used to create the foam roadway for the trafficability experiments. The machine was dispensing 3.5-4.0 lb/ft^3 foam at an average rate of 55 lb/min. Cream time, which is the amount of time elapsed before the mixture reached a cream-like consistency, took place after 55-65 seconds. The foam reached its maximum expansion after a rise time of 3-4 minutes.

Experiment: Two different block sizes, 65" X 65" and 85" X 85", were used in order to investigate edge effects. The PETN explosive was positioned directly underneath the geometric center of each foam block. The top of the explosive was made flush with the sand surface in order maintain direct contact with the block. Nonel Primadet chord, a non-electric blasting device, was used to detonate the charge. The chord made contact with the bottom of the PETN and was routed underneath the sand towards the triggering mechanism. After each shot, measurements were taken of the ground crater, entrance cavity, exit cavity, and depth of penetration in the foam.

Results: The 30- gram explosive perforated through all but the 30-inch foam block. The failure of the foam block was contained to the cavity, and there were no cracks observed laterally to either side of the foam. Two modes of failure were observed on the blocks that were perforated. The direct blast failure results in the crushing of the foam cells near the entry point of the explosive while the foam's mechanical failure results in a shear plug. The shear plug creates an exit cavity significantly larger than the entry cavity. Figure 1 shows a generic sketch of the explosive effects on an RPF block.

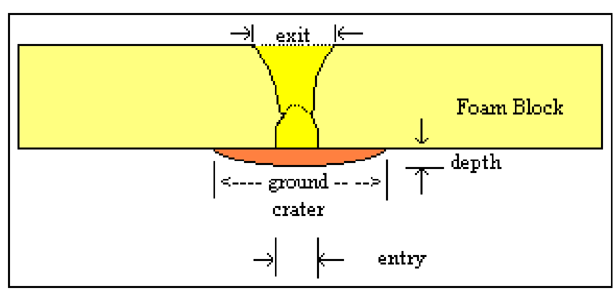

Figure 1. Sketch of the explosive effects on an RPF block.

Using the cube-root scaling equation,

$$D = AW^{1/3}$$

where D is the cavity depth in inches, A is a constant with units $in/g^{1/3}$, and W is the yield in grams, we can calculate the constant, A, in order to predict cavity depths from larger yields. For the 4 lb/ft^3 foam, A has a value of 3.26 in/g$^{1/3}$. This constant allows us to predict both the cavity depth and cavity diameter based on our experimental results. Using these predictions for the 4 lb/ft^3 foam, a VS - 1.6 anti-tank mine, which has 1.7 kg of TNT, would create a 31-inch cavity diameter with a cavity depth of 35 inches. Similarly, the M19 anti-tank mine, which has 9.5 kg of Comp B, would create a 61-inch cavity diameter with a cavity depth of 67 inches. These numbers suggest that in order to completely contain an anti-tank mine similar to the M19, the foam roadway would have to be much greater than 67 inches thick. Additional experiments will have to be conducted in order to obtain a foam density that can provide an operationally capable foam roadway.

Repair of Damaged RPF Blocks

Set-up: The damaged foam blocks used for these experiments were the blocks used for the cavity formation experiments.

Experiments: These experiments were conducted to determine the most efficient method of repairing a damaged foam block and its subsequent strength. By pouring the foam directly into the damaged cavity, some of the foam escaped through the bottom. Once the foam began to rise, it quickly adhered to the interior of the block.

Results: The foam not only filled the cavity, but it also seeped through the smaller cracks in the interior wall. Cold joints were formed at the boundary between the new and old joints. Follow-on experiments will determine the resulting strength of these repaired foam blocks.

Conclusions

The test results gathered from the Waterways Experiment Station indicate that a 24-inch thick, 4 lb/ft^3 Rigid Polyurethane Foam roadway adequately supported multiple passes of a track and wheeled vehicle. More importantly, the foam roadway was able to neutralize the mines buried underneath the foam and activate all trip wire detonated devices in the breach lane. Traction tests revealed that the foam did not improve traction for the M88A2 and only slightly increased the traction of the HMMWV. As for its use as a breaching technique for anti-personnel mines, the foam roadway itself serves as a very efficient breach lane, but it currently can not be employed in the timely manner needed for breaching exercises. The current dispensing machine can not dispense large enough quantities of foam in the required time for a in-stride breach.

The explosive cavity formation tests by Sandia National Laboratories indicate that a blast anti-personnel mine with 30 grams of PETN can be adequately contained by a 16-inch thick, 4 lb/ft^3 foam block. A 10 gram PETN charge can be contained by a 14-inch thick, 4 lb/ft^3 foam block This thickness is reduced when the foam is statically loaded.

The combined results of the two test sites indicate that the same 24-inch thick foam roadway constructed by Waterways should be able to withstand the explosive effects of a 30-gram PETN charge. Based on cube root scaling laws, the 24-inch foam roadway should be able to completely contain a 10-gram PETN charge, and the 30-gram data suggests that the foam roadway could contain a significantly larger charge. Energy absorption experiments are currently being conducted by Sandia National Laboratories in order to determine the amount of energy that is mitigated by the foam. The amount of foam needed to contain a specific explosive can be determined from the energy absorption properties of the foam.

These feasibility experiments indicate that Rigid Polyurethane Foam, at a given density and thickness, can withstand the explosive effects of anti-personnel blast mines and mitigate or neutralize the effects of surface laid anti-tank mines.

The work described here is a summary of a thesis submitted to the Naval Postgraduate School for a Master of Science Degree in Applied Physics. [Ref.14]

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