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Effect of Prill Structure on Detonation Performance of ANFO

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Abstract. While the effects of charge diameter, fuel mix ratio, and temperature on ANFO detonation performance are substantial, the effects of prill type are considerable as well as tailorable. Engineered AN prills provide a means to improve overall performance, primarily by changing the material microstructure through the addition of features designed to enhance hot spot action. To examine the effects of prill type (along with fuel mix ratio and charge diameter) on detonation performance, a series of precision, large-scale, ANFO front-curvature rate-stick tests was performed. Each shot used standard No. 2 diesel for the fuel oil and was essentially unconfined with cardboard confinement. Detonation velocities and front curvatures were measured while actively maintaining consistent shot temperatures. Based on the experimental results, DSD calibrations were performed to model the detonation performance over a range of conditions, and the overall effects of prill microstructure were examined and correlated with detonation performance.

Introduction

The explosive mixture of ammonium nitrate and fuel oil (ANFO) is used primarily for mining and construction, and easily accounts for the majority of explosives used worldwide. ANFO is considered a non-ideal explosive, and is heterogeneous in nature. As a result, the detonation performance of ANFO is highly sensitive to the constitutive ingredients, their proportionate mix, degree of confinement, and environmental factors. Figure 1 summarizes the key physical parameters that affect this overall performance.

For a stoichiometric balance, 94% (by weight) ammonium nitrate (AN) prills are mixed with 6% (by weight) fuel oil (FO), typically standard No. 2 diesel fuel although other common fuels do suffice. Standard explosive grade prills (PPAN, or porous-prilled ammonium nitrate) are primarily used that contain sufficient porosity to make the mixture sensitive to initiation. The term "standard explosive grade" is becoming less and less clear as specialized AN prills are being developed by manufacturers and more commonly used in industry for improved performance.

While all AN prills are chemically the same product, what varies between prill types (whether being standard explosive grade, specialty explosive grade, or even fertilizer grade) is the prill size, the degree and morphology of the included porosity, and how the porosity is created and maintained. These factors (which also determine the prill microstructure) contribute to the overall sensitivity and performance of the explosive mixture in its final form. Modern manufacturing techniques are able to vary the level of included porosity (as well as outer surface coat-

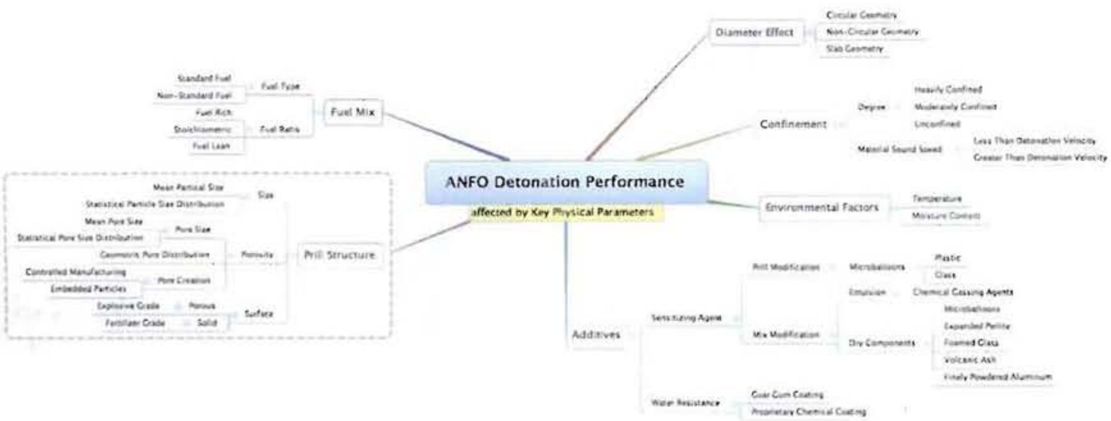

Fig. 1. Physical parameters affecting ANFO detonation performance.

ing) to create prills suitable over the full range of uses from fertilizer to explosive.

In addition to prill refinement, performance additives are regularly added to ANFO mixtures to either sensitize the explosive or to provide benefits such as water resistance. Sensitizing agents such as glass or plastic microballoons, expanded perlite, foamed glass, or volcanic ash may be added to the mix to provide increased hot spot reaction. Emulsions are also used to either mix with the dry prills, or as a pure emulsion blend. Such emulsions also act to increase hot spot reaction via the addition of chemical gassing agents to create small voids in the slurry. For added detonation performance, the addition of other dry components such as finely powdered aluminum has been shown to significantly increase the peak shock pressure of ANFO[1]. For performance enhancements with respect to environmental robustness, water resistant coatings and mixtures using guar gum and other proprietary chemical coatings are common. Though all of these methods serve to increase the performance of ANFO, the current studies have focused on the effect of prill structure.

Experiment

A series of precision, large-scale, ANFO front-curvature rate-stick tests has been performed to examine the effects of prill size, prill microstructure, fuel mix ratio, and charge diameter on detonation performance. Cylinder diameters of 8 and 12 inches were fired in 14 diameter lengths for each material with cardboard confinement (i.e. essentially unconfined). Standard No. 2 diesel was used for the fuel oil in each explosive mixture. Each shot was boosted with 1-2 sheets of C6 Detasheet and initiated with a Reynolds RP-83 detonator.

The detonation front curvatures were measured at breakout at the end of the cylinders via a Cordin 136 streak camera and PETN-based flash paint. The 0.125" wide strip of flash paint was applied across the diameter of the PMMA endplate and then covered with copper tape to block light bleed through the material before the arrival of the main detonation wave. In addition, 10 Dynasen shorting pins (placed one diameter apart beginning one diameter from the endplate) were used to measure detonation velocities along the length of each tube, and a high-speed framing camera was used to visualize the afterburn effects of each shot. Temperature control via heated enclosure maintained consistent experimental conditions for selected shots when necessary. A schematic of the shot assembly is shown in Figure 2.

In addition to testing the standard explosive grade AN prill, specialty prill types were tested including Fragmax (a small diameter, high-density prill manufactured by Dyno Nobel) and Expan (a nominal diameter, low-density prill with encapsulated plastic microballoons manufactured by Sasol Nitro). Fuel mix ratios were varied (between 5% and 6%) for each diameter and type of prill tested. Each of the selected prill types had a significantly different mi-

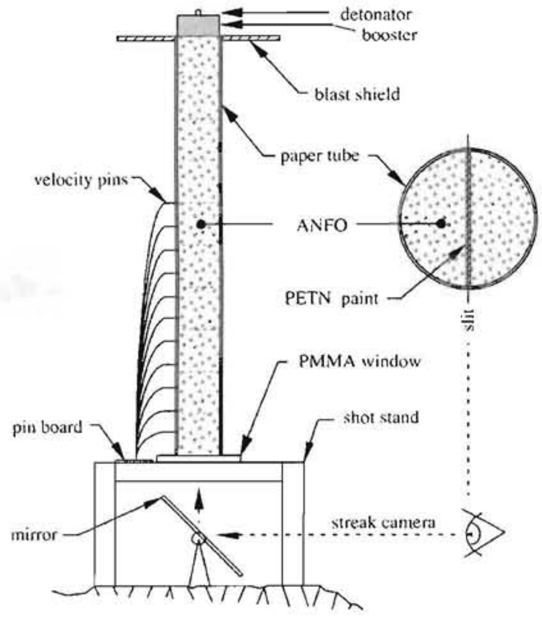

Fig. 2. Schematic of ANFO shot assembly.

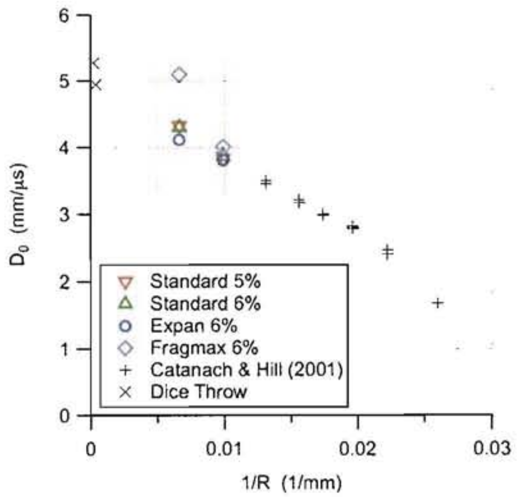

Fig. 3. ANFO diameter effect data.

crostructure, thus allowing performance differences to be measured and correlated to the physical characteristics (both macroscale and microscale) of the explosive mixture.

In addition to three scoping/calibration shots, a total of eight large-scale ANFO shots were fielded for the current test series at the Energetic Materials Research and Testing Center in Socorro, New Mexico. Table 1 summarizes the experimental shot parameters and measured detonation velocities from the shot series.

Detonation Performance

Diameter effect data from the shot series is depicted in Figure 3. Other large-scale ANFO shot results are also shown for comparison including similar tests performed by Catanach and Hill[2]. For the current shot series, the standard grade PPAN results lie very near the established curve for this material as expected. The specialty Expan and Fragmax material results deviate from the established curve with respect to both speed and diameter curve slope. For the diameters tested, the 12" diameter Fragmax shot deviates most dramatically in performance.

To obtain the detonation front curvatures, the films capturing the wave breakouts for each shot were first optically scanned. After digitizing the films, the actual wave shapes were determined through knowledge of the optical system magnification, the camera write speed, and the detonation velocity (as determined by the shorting pins).

DSD Calibration

For DSD predictions of a non-ideal explosive such as ANFO, characterization of the performance effects detailed in these experiments is necessary to represent such heterogeneous behavior. The current series results (in combination with the results from previous studies[2]) have been used to model ANFO with good success[3,4].

To fit the experimental front curvature data, the Hill fitting form[2]

$$z(r) = -a \ln \left[\cos \left(\frac{\eta \pi r}{2R} \right) \right] \quad (1)$$

was used where r = radius, R = charge radius, and a and η are fitting parameters. Table 2 lists the DSD calibration parameters used to fit entire shot series.

DSD D_n-κ fits to the shot series using the Hill fitting form are plotted in Figure 4. Unlike calibrations for an ideal explosive where D_n-κ fits overlay for different diameters, the results from the non-ideal ANFO tests do not. Again, the Fragmax shot results deviate the most, exhibiting higher detonation velocities in general.

Table 1. ANFO shot parameters and measured detonation velocities.

Shot Number	Prill Type	Fuel Mix (%)	Temperature (C)	Density (g/cc)	Diameter (mm)	Detonation Velocity (mm/μs)
4	Standard	5	21.5	0.883	203.2	3.836
6	Standard	5	24.5	0.897	304.8	4.329
5	Standard	6	19.5	0.900	203.2	3.876
7	Standard	6	19.5	0.903	304.8	4.308
8	Expan	6	23.5	0.793	203.2	3.819
11	Expan	6	29.5	0.807	304.8	4.116
9	Fragmax	6	25.0	1.168	203.2	4.014
10	Fragmax	6	24.5	1.169	304.8	5.093

Table 2. ANFO shot DSD calibration parameters for Hill and linear fitting forms.

Shot Number	Prill Type	Fuel Mix (%)	a (mm)	η	Edge Angle (deg)	D_{CJ} (mm/μs)	B (mm)
4	Standard	5	19.72	0.788	34.98	5.003	29.06
6	Standard	5	28.53	0.765	29.95	5.003	29.06
5	Standard	6	29.93	0.676	29.54	4.902	26.67
7	Standard	6	43.24	0.643	24.93	4.902	26.67
8	Expan	6	18.75	0.790	33.17	4.404	18.00
11	Expan	6	32.29	0.698	24.38	4.404	18.00
9	Fragmax	6	31.53	0.680	31.28	6.795	47.50
10	Fragmax	6	41.52	0.715	32.34	6.795	47.50

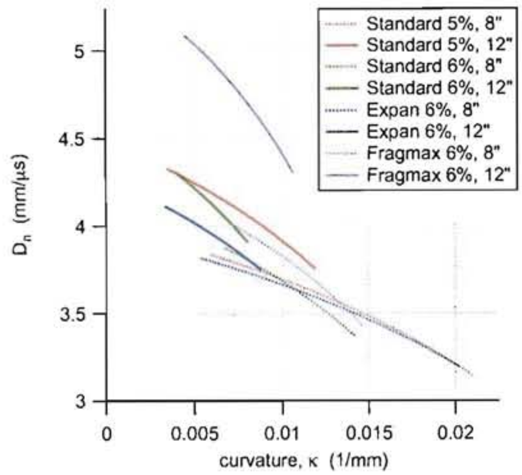

Fig. 4. DSD D_n-κ fits via Hill fitting form.

Due to the heterogeneous nature of the non-ideal ANFO mixture, scatter in the DSD fits are evident as seen in Figure 4. For a simplified DSD calibration[3], a linear D_n-κ fitting form

$$D_n = D_{CJ}(1 - B\kappa) \quad (2)$$

may be used where D_{CJ} and B are fitting parameters. Table 2 also includes the DSD linear fitting parameters determined for the entire shot series. Via this method, it is possible to predict the C-J detonation velocities for each of the materials tested. The linear D_n-κ fits are plotted in Figure 5.

Also through the use of the linear D_n-κ fits, it is possible to predict the diameter effect curves for each of the materials tested. Figure 6 depicts these curves, along with the experimental diameter effect data. The Fragmax material displays the largest failure diameter, while the microballoon laden Expan material displays the smallest failure diameter, though its detonation velocity is lower.

Front curvature fits also based on the linear D_n-κ calibrations are plotted in Figure 7. The shapes of these fronts help to visualize the relative non-ideality of the tested ANFO materials, as well as the obvious effect of diameter on detonation performance.

Prill Microstructure

While the DSD calibrations allow for the relative performance of the various ANFO mixes to be eval-

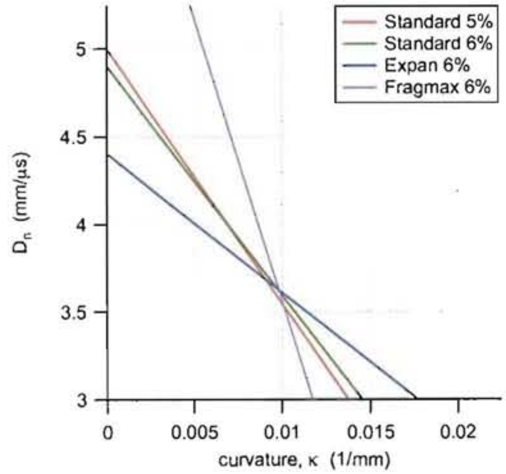

Fig. 5. DSD linear D_n-κ fits.

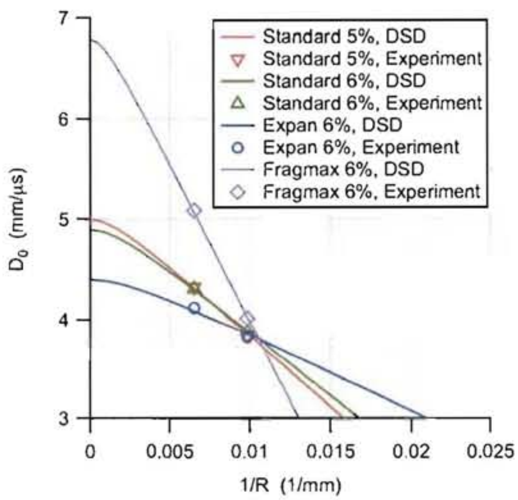

Fig. 6. DSD predicted diameter effect curves via linear D_n-κ fits.

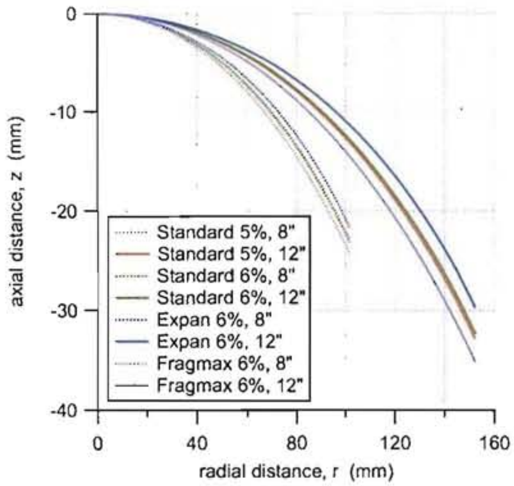

Fig. 7. DSD linear D_n-κ front curvature fits.

uated, the specific material properties of each mixture need to be addressed. More specifically, examination of the microstructure of each prill type is necessary.

On a macroscopic level, prill size and prill size distribution have measurable effects on detonation performance. In an attempt to increase explosive density and performance, manufacturers such as Dyno Nobel have created smaller, high density prills. The Fragmax prills tested in the current series can be seen in the photographs of Figure 8. The upper photo shows the relative size differences between Fragmax and the standard PPAN material. The lower photo shows the material as tested, where smaller random size particles included in the mix are evident.

On a microscopic scale, pore size and pore distribution have measurable effects on detonation performance as well. Manufacturers have exploited this fact as an avenue for increased detonation performance. Specifially, Sasol Nitro has created the Expan material with embedded plastic microballoons to increase hot spot action. Though the void space created by the microballoons is non-accessible to the fuel oil, the remainder of the AN material contains fuel accessible pores.

An SEM photo comparison between standard PPAN material and Expan is shown in Figure 9. Both microstructures exhibit similar void space

Fig. 8. Prill photos demonstrating size differences between standard explosive grade PPAN and Fragmax specialty prills. (Upper photo taken by manufacturer Dyno Nobel.)

throughout the bulk of the material, but the lower Expan photo also indicates the additional embedded microballoons. Clearly evident from the results presented in this study, the presence of these microballoons has a dramatic effect on explosive performance.

Analysis

The results of the tests indicate significantly different performance behavior between each type of ANFO material with respect to detonation velocity, front curvature, detonation edge angle, and failure diameter. These differences are indeed dependent on the microstructure and physical characteristics of the AN prills (in addition to the performance differences due to fuel ratio).

Note that the Fragmax-based ANFO (with the smallest prill size) has been determined to behave more ideally, with a higher detonation velocity and a steep diameter effect curve (similar to a more homogeneous explosive). In contrast, the Expan-based ANFO behaves more like a truly heterogeneous explosive, with a detonation velocity even lower than the standard PPAN-based ANFO. Beneficially, the failure diameter for the Expan-based

ANFO is predicted to be the smallest of the materials tested. These performance differences are related to the macro and microstructure of the prills as well.

Conclusions

From the series of large-scale ANFO shots fielded, detonation performance trends based on AN prill type, fuel mix ratio, and diameter have been examined. The results of such experiments allow for intelligent modeling of ANFO detonation performance over a range of material parameters. DSD calibrations have been performed using both the Hill front curvature fitting form[2] and a simplified linear D_n-κ relation. Based on the linear method, diameter effect curves have been predicted for each material, thus allowing C-J detonation velocities to be estimated as well.

Beyond the successful modeling of ANFO detonation performance, the material questions remain about how AN prill microstructure affects performance. By examining the structure of each type of prill both microscopically and macroscopically, valuable insight has been gained into the material effects on ANFO detonation performance.

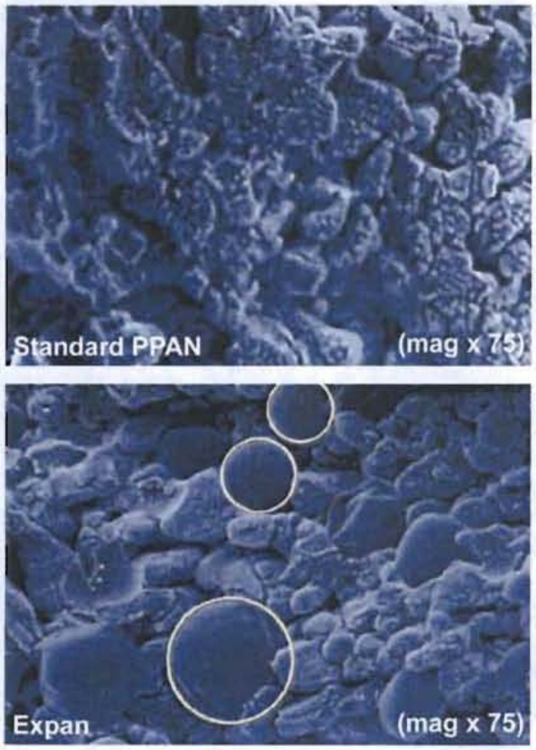

Fig. 9. SEM photos demonstrating microstructure differences between standard explosive grade PPAN and Expan specialty prills. Expanded microballoons embedded in crystal structure are indicated in lower photo. (Photos taken by manufacturer Sasol Nitro.)

Acknowledgments

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References

1. Johnson, J. N., Mader, C. L. and Goldstein, S., "Performance Properties of Commercial Explosives," *Propellants, Explosives, Pyrotechnics*, Vol. 8, pp. 8–18, 1983.

2. Catanach, R. A. and Hill, L. G., "Diameter Effect Curve and Detonation Front Curvature Measurements for ANFO," in "12^{th} American Physical Society Topical Conference on Shock Compression of Condensed Matter," pp. 906–909, APS, 2001.

3. Bdzil, J. B., Aslam, T. D., Catanach, R. A., Hill, L. G. and Short, M., "DSD Front Models: Non-Ideal Explosive Detonation in ANFO," in "12^{th} International Detonation Symposium," pp. 409–417, ONR, 2002.

4. Short, M., Salyer, T. R., Aslam, T. D., Kiyanda, C. B., Morris, J. S. and Zimmerly, T., "Detonation Shock Dynamics Calibration for Non-Ideal HE: ANFO," in "16^{th} American Physical Society Topical Conference on Shock Compression of Condensed Matter," pp. 189–192, APS, 2009.