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Research paper

Preliminary Detonation Study of Dry, Wet and Aluminised ANFO Using High-Speed Video

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Abstract: ANFO is a well-known, reliable and safe commercial explosive. It has been around since the late 1950's and its detonation properties are well characterized. In this study, the detonation process of dry, wet and aluminised ANFO, was recorded using two high-speed cameras with recording rates of 1,200 fps and 50,000 fps. The 1,200-fps footage allowed the observation of the post blast fumes (*i.e.* NOx) produced by ANFOs with different water contents. The 50,000-fps footage allowed the observation of the detonation area, gas expansion phase and the measurement of the velocity of detonation (VOD). The video footage also recorded a bright zone in front of the gases (longer than 50 mm). We assumed that a reaction is taking place in this zone, but it is difficult to be sure if this is the reaction zone or not as it is longer than previously reported reaction zone lengths.
Analysis showed that ANFO detonates effectively for water contents of up to 9 wt.%, and more importantly, there is little variation in the VOD. As far as the expansion of gases is concerned, the ANFO-Al expansion rate appears to be different. In this mixture, the absence of NOx fumes could have been due to the expected higher temperatures produced by the burning of the aluminium additive as observed in the images recorded with the high-speed camera.

Keywords: ANFO, detonation, high-speed video, aluminised ANFO, nitrogen oxide fumes, velocity of detonation, non-ideal explosives

Nomenclature:

AN	Ammonium nitrate
ANFO	Ammonium nitrate – Fuel Oil explosive
fps	Frames *per* second [1/s]
NOx	Nitrogen oxides

1 Introduction

Ammonium Nitrate – Fuel Oil (ANFO) is the most well-known explosive in the mining, quarrying and civil construction industries due to its simplicity, safety and cost. The detonation properties of ANFO were first studied in the 1960's by Yancik [1]. Further studies on aluminised ANFO have also been reported by various authors [2-5], and in the case of wet ANFO, by Hurley [6].

With the advent of lower cost and high-fidelity digital video technology, and particularly high-speed video cameras, it is now much easier and accessible to study fast physical-chemical processes such as the detonation of an explosive charge [7-9]. With this technology, there was an opportunity to revisit past studies on ANFO and conduct an analysis of the detonation process at high recording rates (*i.e.* 50,000 fps) and also observe at lower recording rates (1,200 fps) the NOx fumes produced by the detonation. This paper describes the results of preliminary and unique observations when water or aluminium is added to ANFO mixtures.

2 Experimental Section

2.1 Formula

ANFO made from porous prilled AN (with an untapped density of 0.75 g/cm^3) and commercialized by Extech (Australia), was sourced for the tests. For the straight ANFO test (no water), the product was used without further treatment. For the ANFO-water tests, 3 wt.%, 6 wt.% and 9 wt.% of water was sprayed on the ANFO product whilst being rotated in a 20-L plastic container. The aim of this procedure was to make sure a homogenous mixture of water and ANFO was achieved. For the ANFO-Al tests, aluminium shavings (rather than granules or powder) were blended with the product in a similar fashion.

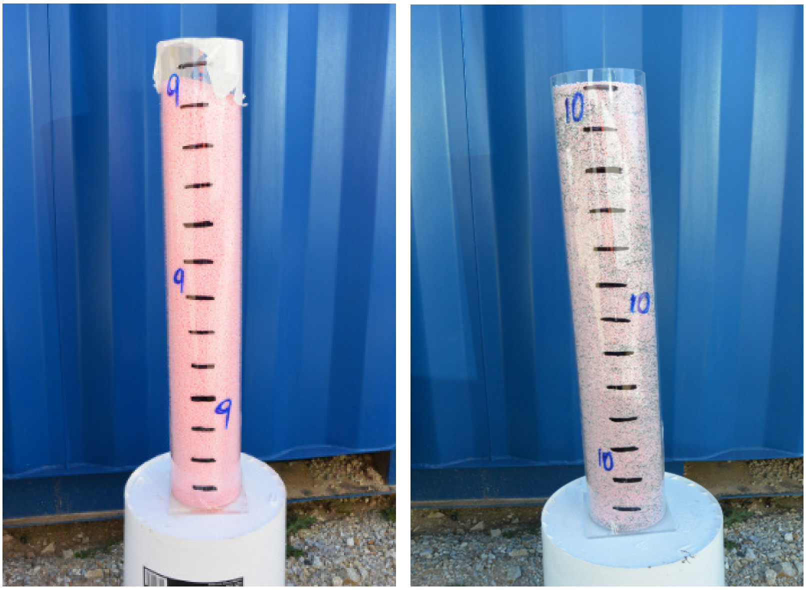
The density of each ANFO-water sample was measured. It is worth noting that two values for the densities were measured: the tapped and untapped cases. The untapped density is not accurate in these tests, as water renders ANFO prills stickier, preventing ANFO from flowing properly. This causes the formation of voids in the cup density, causing error in the measurement. Therefore, the tapped density was adopted as it provided a more realistic value for the density of the charges. Table 1 displays the values measured for each parameter.

Table 1. ANFO-water formulas

ANFO [g]	Water [g]	Aluminium [g]	Density [g/cm^3]		Water [%]		Al, dry basis [%]
			untapped	tapped	dry basis	wet basis	
4500	0	0	0.78	0.85	0	0	0
4500	135	0	0.77	0.85	3	2.9	0
4500	270	0	0.83	0.87	6	5.7	0
4500	405	0	0.80	0.86	9	8.3	0
4500	0	180	–	–	–	3.8	4

Note that the type of ANFO used in these tests did not allow water incorporation beyond 10-11%. During the preparation of the ANFO sample with 12% of water content, the 20-L plastic container, where the sample was prepared, had a pool of water at the bottom, indicating that the ANFO was saturated and unable to absorb more water. In these preliminary experiments, it was not deemed necessary to conduct specific tests to exactly determine the maximum water absorption of the available ANFO product.

All the ANFO samples were fired within 60 min of preparation. Dry, wet and aluminised ANFO samples were loaded into 105 mm inner diameter, 700 mm long clear acrylic pipes. The total amount of ANFO in the pipe was approximately 4.5-5 kg. The ANFO samples were initiated with a detonator and 150-g boosters (made of PETN/RDX/TNT) supplied by Beston Australia. Figure 1 shows two ANFO samples used in this study, ANFO with 9% water and 4% aluminium shavings, respectively.



(a) (b)

Figure 1. ANFO charge with 9% of water (a) and ANFO with 4% of Al (b)

The marks seen on the pipes are 50 mm apart. They were used as reference points to measure the VOD using the video frames obtained with the high-speed video.

2.2 Instruments

The high-speed video of the detonation front was recorded with a Photron Fastcam SA-X2 high speed camera. The camera was located 20 m from the explosive charges, protected by a plywood screen having a square cut hole in which a 20 mm thick clear polycarbonate sheet was placed to protect the camera lens. The camera was enclosed to protect it against the near field air blast overpressure. The frame rate to capture the detonation was set to 50,000 fps (*i.e.* a frame was captured every 20 µs) with a resolution of 768×328 pixels. Frames of this video footage were used to observe the detonation region, measure the angle of expanding gases and to calculate VOD (a detailed description for the VOD measurement technique is given in section 3.2).

To record the overall plume of gases emerging from the detonation, a Nikon 1 J1 camera was used and set at a framing rate of 1,200 fps (with a resolution of 320×120 pixels). This camera was placed approximately 200 m from the blasting area.

In the test program, charges were suspended and therefore completely unconfined. Figure 2 displays a typical set up for the detonation test (note that the picture belongs to another test, and it is used here for illustrative purposes).

Figure 2. Test set up

3 Experimental Results

3.1 High speed video showing the detonation region

Selected frames of the detonation region recorded with the Photron Fastcam SA-X2 camera are shown in Figure 3. The numbers shown on the pipes (*i.e.* 2, 3, 4, 9 and 10) refer to the order of firing the samples during the test day not to the water content (different tests were also conducted at the same time).

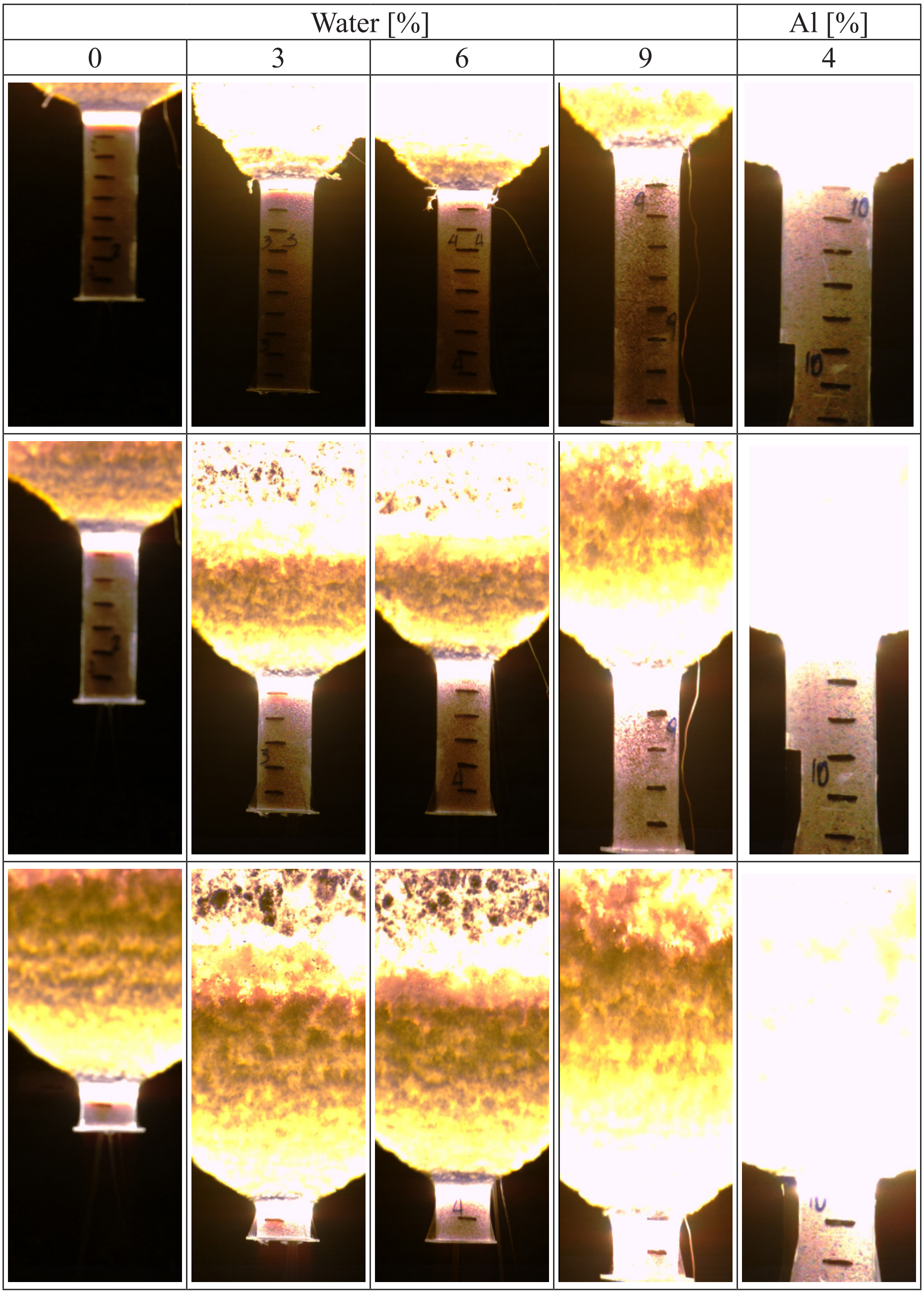


Figure 3. Detonation frames

Some interesting features can be observed when looking closely at the still video frames for the different samples. Firstly, the area in front of the expanding gases is significantly bright. Secondly, the intensity of the light for the zone above in both ANFO with 9 wt.% water and ANFO with 4 wt.% aluminium appeared much brighter than for ANFO charges containing less water. It was also noted that this bright zone is more consistent in shape for dry ANFO samples. It appears that as water was added, a more irregular bright zone developed; and the bright zone grows in length as the water content increases.

3.2 VOD and expanding gases of the ANFO charges

The high-speed video images allowed the measurement of both the VOD and the angle formed between the pipe and the expanding gases. The VOD was measured by marking two consecutive still frames at the beginning of the expansion of the gases and then measuring the distance between those marks. A sample of the marks in the images is displayed in Figure 4 (Frame_9 and Frame_10). The pipes had already had lines drawn on them every 50 mm as reference marks to calculate the distances in the still frames.

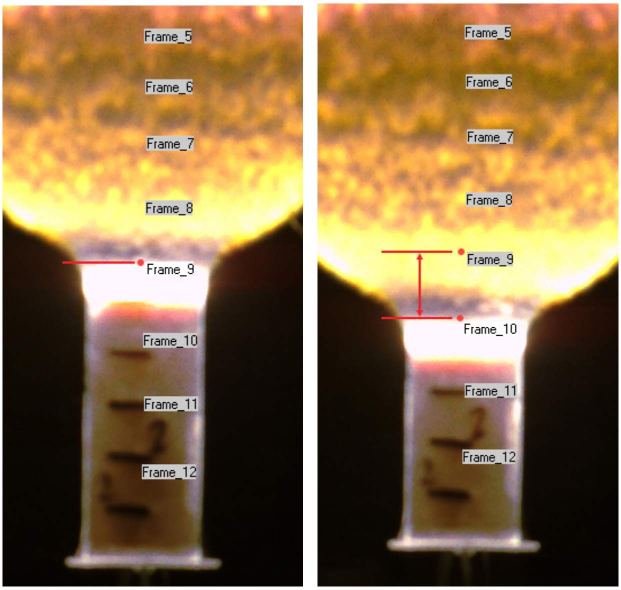


Figure 4. Marks in the still frame for VOD measurement

Figure 5 displays a VOD plot sample obtained by measuring the distance travelled by the detonation in a fixed time (20 μs between frames for a framing rate of 50,000 fps). At least 8 frames (which produce 7 points in the plot) were available to measure the VOD for all the ANFO samples, but more importantly, the points allowed the observation of both the run-up and the steady VOD of ANFO (the flat part of the curve, after 80 μs). Note that the VOD for the ANFO samples was calculated by averaging the last 3 points of the plot (*i.e.* where ANFO reaches its steady VOD). The variation of the VOD, that in some cases is around 10-15 between points, could be due to the accuracy of the measurements conducted in the still frames. However, Lozano *et al.* [7] found a similar variation in their tests.

The angle of the expanding gases was measured according to Figure 6. Table 2 displays a summary of the results using the data from the high-speed video footage, *i.e.* VOD, angle of expanding gases and length of the bright zone.

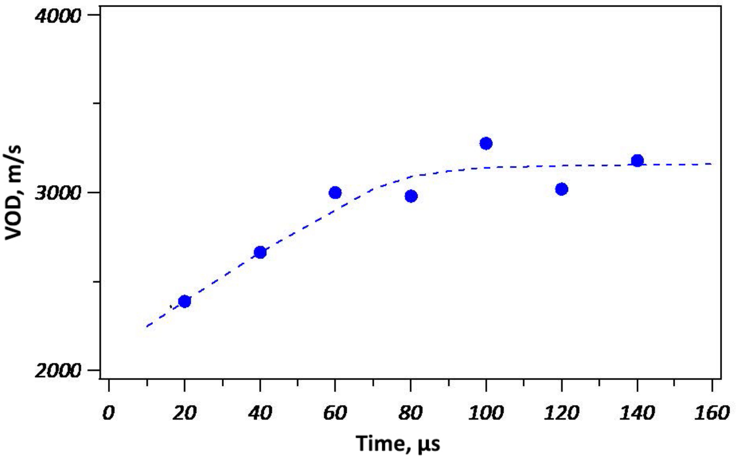


Figure 5. VOD measured from high speed still video frames for ANFO (● – results of calculations)

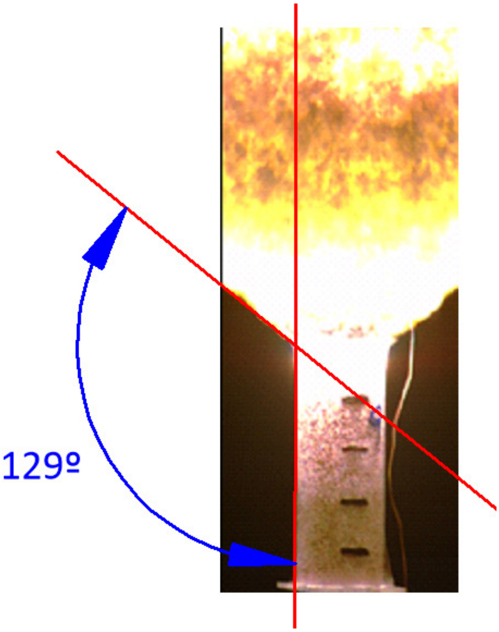


Figure 6. Angle measurement definition

Table 2 Data for the samples tested

Content [%]	VOD [m/s]	Angle of expanding gases	Bright zone [mm]
0 (Water)	3130	136	41
3 (Water)	3160	128	45
6 (Water)	3200	128	52
9 (Water)	3210	129	80
4 (Al)	3060	118	66

Analysis of the data shows a preliminary trend in the gas expansion angle, where the angle of expanding gases for the ANFOs is larger than for the aluminised ANFO. The values of the angle for the wet ANFOs lie between those for the dry and aluminised ANFO. A plot summarising both the measured VOD and the bright zone length obtained from the high-speed camera footage is given in Figure 7.

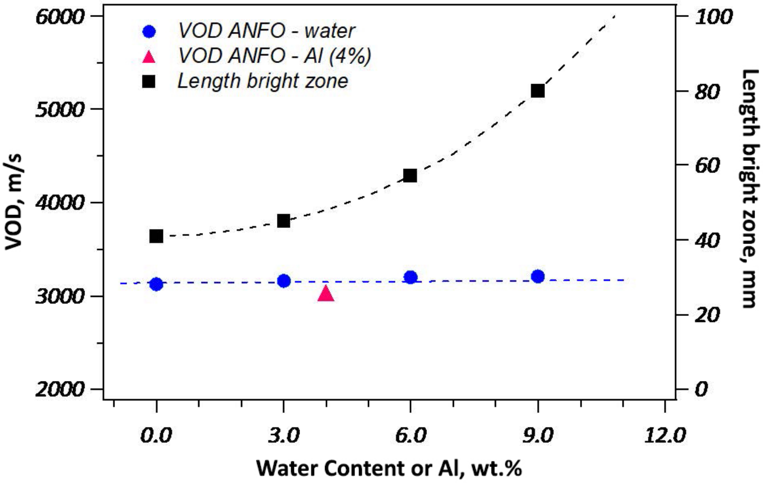


Figure 7. VOD and bright zone length measurements using still frames

Based on these preliminary experiments, the VOD for ANFO can be seen not to be influenced by the presence of water (or at least the difference is not very significant) and therefore can be said to remain constant in the range 0-9 wt.% water. The addition of aluminium seems to have a marginal influence on the VOD for ANFO. In the case of the bright zone, it was observed that its size grows with an increase in the water content.

3.3 Observation of gas plume

Figure 8 shows the detonation of the ANFO samples recorded at 1,200 fps. The first column at the left-hand side indicates the water or Al content of the sample. Note that the detonation of ANFO containing 3% water was not captured. The video footage shows the generation of NOx fumes in both ANFO and wet-ANFO products (the NOx release being higher for the ANFO with 9% water), and, in the case of aluminised ANFO, the detonation appears to be brighter and the NOx fume evolution minimal.

It is important to note that all the ANFO samples had the same VOD (see Table 2), but that during detonation, it was observed that the detonation of the sample with 9% water was stronger (a conveyor mat under the explosive charge was lifted around 3 m above the ground during the detonation).

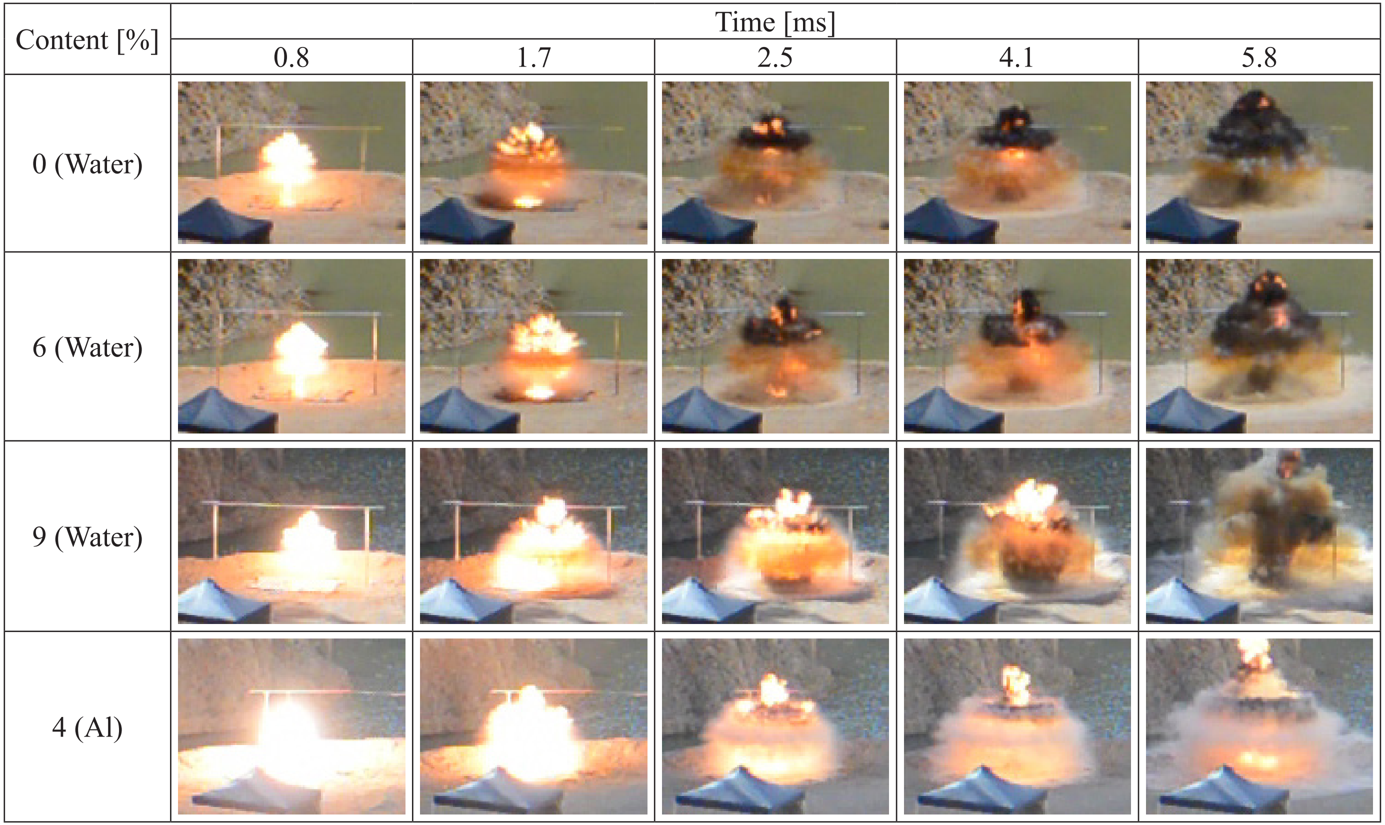


Figure 8. Analysis of the gases of detonation using 1,200 fps video camera

4 Discussion

4.1 Water content and VOD of samples

Results from this preliminary study showed that the VOD of ANFO does not vary significantly with an increase in water content up to 9 wt.% (see Table 2, column 2). These results agree with the research performed by Hurley [6], although that study was conducted using crushed rather than prilled ANFO.

It was not possible to test an ANFO product with a 12% water content, as during the preparation it was noticed that water load was too high for the ANFO to absorb, and the excess water accumulated at the bottom of the container. As displayed in Table 1, the density of the samples did not vary much (0.85-0.87 g/cm^3), even for those with a high-water content.

This lack of VOD variation in the ANFO samples with an increase of water contrasts with the study conducted by Yancik in the 1960's, when ANFO technology was in its infancy [1]. In that study, a water content of 7-8 wt.% caused the ANFO VOD to drop by approximately 12-14%, and in the case of 9 wt.% water, the VOD drop was significant (*ca.* 38-40%). The differences in these results may be associated with differences in prill characteristics. The AN prill used to prepare the ANFO in this study (and probably also in Hurley's study [6]) could have had a higher porosity and thus have been more sensitive to initiation (regardless of the water content) than the AN prill manufactured in the 1960's.

However, it is acknowledged that the presence of water in the ANFO used in this study, in percentages above 10% or higher, may cause a detonation failure, as in the study conducted by Yancik [1].

It is important to highlight that when ANFO is used in the field, the conditions vary from day to day, so care should be taken when extrapolating the results obtained in this study to ANFO used in the field.

Surprisingly, in addition to the absence of a VOD variation with an increase in water content, it was observed that the detonation of ANFO with 9% water appeared to be more energetic than other samples which contained less water. This would need further study, in which pressure sensors, double pipe tests and steel plates should be used to determine the strength of the detonation for this type of sample.

4.2 Aluminium influence in VOD of ANFO

In the case of ANFO with 4% aluminium, the VOD observed was slightly lower than for ANFO samples. Previous studies conducted by Katsabanis *et al.* [3], found that Al with a small particle size increased the VOD of ANFO. The different size of Al used in Katsabanis' work and in this study seems to indicate that aluminium particles of different particle size could react at different stages in the process of detonation and hence influence the VOD. Small aluminium particles could quickly react at the detonation front and contribute to the VOD, while large aluminium particles could react more slowly as the size increases – the reaction could even take place even behind the CJ plane, in which case there would be no contribution to the VOD by the aluminium. That seems the case for the results obtained in this study. It could be anticipated that for extremely large aluminium particles, the VOD could drop due to the fact that the particles could dilute the ANFO energy. Further studies are required to support this hypothesis.

4.3 Angle of gas expansion

The goal of this study was to observe the detonation zone of ANFOs with different amounts of water. However, after analysing the video footage, it was found that the angle produced by the gas expansion (see Figure 6) followed an interesting trend. The angle for aluminised ANFO was smaller (118º) than the angle produced by the dry ANFO sample (136º), and both had nearly the same VOD.

It is known that aluminised ANFO contains more energy than ANFO (see for example the work in the aquarium test conducted by Goldstein *et al.* [10]), so the question is whether the angle of the expanding gases gives some information about the energy content and release.

Note that the expanding gas angles for samples of ANFO containing water (around 128-129º) were located between dry ANFO and aluminised ANFO. It is suggested further studies be performed in this area.

4.4 Bright zone

One of the most interesting observations in this study was the presence of a bright zone in the detonation zone (*i.e.* 41 mm in the case of ANFO with no water – see Table 2). Figure 7 displays this bright zone and the different zones seen during the detonation process. The frame selected was taken 180 µs after initiation for ANFO containing 6% water. The image is sharp enough to see the unreacted prill in front of the detonation front.

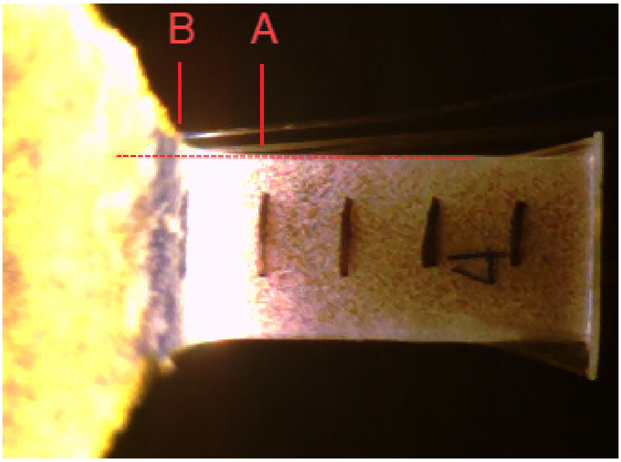


Figure 9. Bright zone observed in ANFO with 6% of water

Lines A-B indicate the bright zone observed during the detonation. The dimension of this bright zone is approximately 50-52 mm. The intensity of the light in this zone suggests that a reaction is taking place. It could be argued that the bright zone could be the reflection of the high temperature expanding gases, especially for the ANFO samples containing 9% of water or with aluminium (see rows 2 and 3 in columns 4 and 5 of Figure 3). On the other hand, samples with no water, 3% and 6% of water, where the expanding gases do not emit an intense light, the bright zone is still present and well defined (rows 1 to 3 from columns 1-3 in Figure 3). The presence of this zone may suggest that the bright zone is also present in the ANFO sample having 9% of water and aluminised ANFO but it is obscured by the flash of white light emitted by the gases. Whether this zone with a bright light is a reaction zone or not cannot be determined at this stage, as the length of bright zone (for the sample containing 6% water) is almost 1.5-2.0 times longer than the length reported in previous studies (between 26-36 mm, Souers [11]). In the case of a sample containing 9% water the length of this zone is 80 mm.

Another explanation is that this bright zone is the product of the light from the ANFO reaction zone filtering forward. In this case, it can be assumed that the reaction zone is located to the left-hand side of "B". As AN prills are opaque to light, any light emitted by the reaction zone would travel in the direction to "A" for only a couple of mm through the prills and will decay very quickly. That light would not reach the line "A". This seems not to be a feasible explanation.

Lozano *et. al*, in their ANFO Aquarium studies [7] also found a bright zone around the detonation front. However, the zone that they observed was shorter in length than the one described in this study. It is suggested that further studies be conducted to determine if the bright zone seen in this study is the reaction zone or not.

4.5 NOx production

The 1,200-fps high speed camera allowed the observation of NOx fume generation during detonation in ANFO samples both with and without water (see Figure 6). However, the footage did not allow the determination of any difference in NOx fumes evolution among the samples. In the case of the Al as an additive in ANFO, NOx fume production was not observed, or at least, the quantity of fumes produced was lower than that in dry or wet ANFO tests. Maranda *et al.* [5] and Sapko *et al.* [12] also found that the addition of aluminium reduced NOx production in a controlled chamber. Most likely the higher temperature reached by the aluminium during the detonation helped with the conversion of NO_3^- to N_2.

The important point here is that the colour of the gases, which can be observed at 1,200 fps, can provide more information about the detonation process when changing parameters such as diameter, density, *etc*. A high-speed camera, with a better frame resolution and higher speed (1080×720 pixel resolution and 5,000 fps, for example) could help with better understanding the generation of NOx in these types of tests. Conversely, the use of a 50,000-fps camera, focused mainly on the detonation process, did not reveal any difference in the NOx fumes production.

5 Conclusions

High-speed digital video has become an important tool to understand the detonation process and performance of non-ideal explosives. The 1,200 fps video footage proved to be useful for the observation of NOx gases (based on colour) produced during the detonation.

The 50,000-fps high-speed camera assisted in observing the detonation process. The footage allowed the determination of the angle formed by the expanding gases. It was found that this angle measurement was different between samples – the aluminised ANFO angle, which should be the most energetic sample, displayed the smallest angle. Further studies are required to confirm this.

The VOD of the samples was obtained by measuring the distance travelled by the detonation front between each frame. The analysis allowed the estimation of the run-up VOD for the samples. Results showed that ANFO with water is still able to detonate with up to 9% of water and the VOD does not vary significantly in the range 0-9% water, in 105 mm diameter unconfined clear pipes. It is recommended that further studies be conducted in this area, potentially including tests under increased confinement.

For the aluminised ANFO test, it was found that the VOD was slightly below the VOD of ANFO. This observation could be explained by the presence of the aluminium shavings which seem to slowly react and, at the same time, dilute the ANFO sample.

Detailed images taken at 50,000 fps allowed the observation of a bright zone (in some cases with a length of 80 mm) which has not been described in previous articles. It is suggested that a reaction is taking place, but its length does not agree with the measured length of the ANFO reaction zone from previous studies. Further work in this area is recommended, to determine the origin of the zone and offer a clear explanation of its characteristics.

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