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Measurement, interpretation and meaning of performance parameters of explosives in blasting applications

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MEASUREMENT, INTERPRETATION AND MEANING OF PERFORMANCE PARAMETERS OF EXPLOSIVES IN BLASTING APPLICATIONS.

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1.0 INTRODUCTION

Commercial explosives are used in rock fragmentation applications and their performance is intimately related to the fragmentation and throw of the rock mass. Malfunction typically penalizes vibrations and/or fragmentation while explosives selection for a specific blasting operation is related, among others, to performance.

Velocity of detonation, detonation pressure and energy are typical explosives parameters which are frequently requested by users of commercial explosives. These are measured in the laboratory but there is a trend today to measure these parameters in the field in order to assess the influence of site variables on the performance of explosive compositions. The purpose of this paper is to interpret measurement for the practical purpose of blast design.

It has been quite common to evaluate blast design using post analysis. Fragmentation results and vibration levels are often used in order to classify the blast as a success or failure. These techniques might be adequate in the case of obvious problems but the average blast has little to gain. Optimization occurs when blast parameters are measured and their interaction is understood. This, due to the transient nature of the process, requires fast data acquisition and accurate knowledge of performance and timing. Data collected might be performance parameters, timing, optical evaluation and vibration.

In this paper the emphasis is placed on the monitoring of the explosive and parameters associated with the detonation of it in boreholes

2.0 VELOCITY OF DETONATION

Velocity of Detonation is the speed of the shock wave associated with the detonation of an energetic material. This wave is associated with the amount of reaction that occurs inside the so-called detonation head. In the case of commercial explosives, reactions occur behind the detonation head contributing to the expansion of the gases without contributing to the speed of detonation. Thus the Velocity of Detonation is a characteristic value of a particular explosive related to the geometry, confinement, state and effective particle size of the explosive; furthermore since it is only affected by the fraction of material reacting in the detonation wave, it provides a good indication of the partition of the total energy of the explosive into shock and heave components. The detonation pressure is related to the detonation velocity by the relationship

$$P_d = \frac{\rho D^2}{4} \tag{EQ 1}$$

where ρ is the initial density of the explosive and
D is the detonation Velocity.

In a case of a coupled borehole, the borehole pressure is:

$$P_e = \frac{P_d}{2} \tag{EQ 2}$$

Therefore knowledge of the velocity of detonation provides information on the quality and consistency of the explosive and the maximum pressure in the borehole. Variations of this property in the case of a the same composition, geometry and confinement occur due to environmental and field parameters.

The measurement of the Velocity of Detonation can be continuous or discontinuous. Continuous systems use continuous resistance probes with constant current power supplies, time domain reflectometry (TDR) or frequency of electrical resonance (SLIFER). Discontinuous systems involve the use of electrical or fiber optic pins.

A continuous system can provide significant amounts of information beyond the simple VOD measurement. Timing information of the detonation of various charges, obtained when multi-channel monitoring is employed, is essential in understanding the sequence of the blast and the interaction between explosives and shock waves. Figure 1 shows the velocities of detonation obtained in a quarry shot using 9 holes with a diameter of 160mm and various products. It is obvious that the fourth hole detonated at a low velocity, something that was verified by the breakage of the burden of the hole as observed from a high speed film of the blast. Table 1 presents the delay times between the holes as observed from the VOD monitoring and high speed photography. It is worth noting that a 325ms delay was used in each hole of the blast while the surface delay was 42ms, except for the last hole which had a surface delay of

TABLE 1. Actual vs. Nominal Delays in a Quarry Blast

Holes	Nominal Delay Difference, ms	Actual Delay Difference, ms	Delay Difference from camera, ms
1-2	42	33.4	34
2-3	42	39	40
3-4	42	41.1	47
4-5	42	19.3	14
4-6	42	45.3	46
6-7	42	31.1	32
7-8	42	33.7	34
8-9	42	93.5	94

100ms. I It is also interesting to notice the actual delay differences obtained by the system and the camera versus the nominal delay difference. Due to the slow detonation of hole #4, a significant error appears in the assessment of the delay of hole #5 by high speed photography. This is due to the fact that timing information from high speed photography is obtained from the flash produced by a piece of shock tube connected to one of the primers in the borehole. In the case of a typical fast detonation the shock tube is continuously initiated by the detonating explosive. In the case of a slow detonation the part of the shock tube outside of the borehole will detonate some time after the initiation of the borehole.

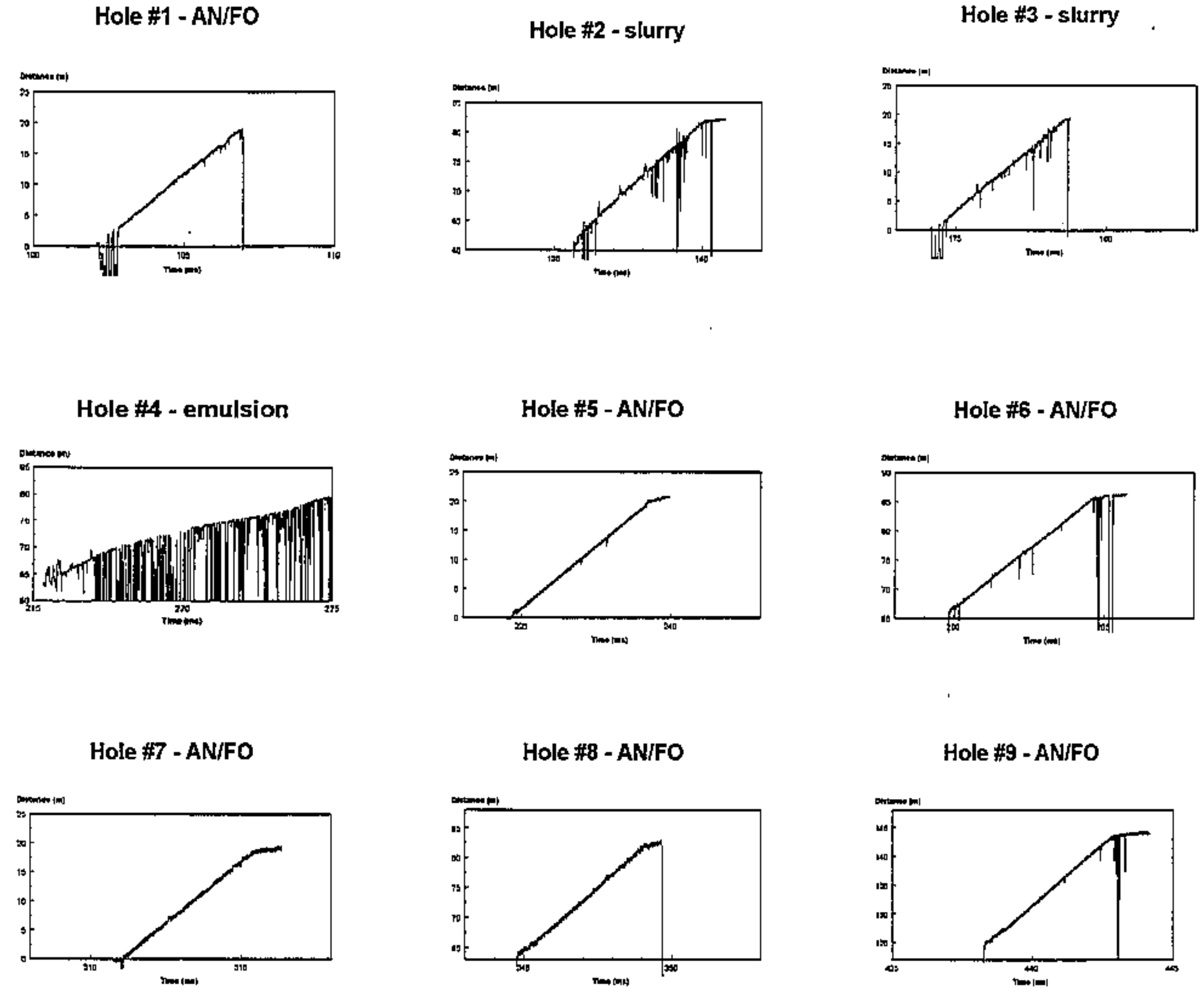

Figure 1: VOD records from a quarry blast.

It is worth noting that the scatter is not as significant as a first glance would indicate. It is well known that the standard deviation of the delay times are proportional to the nominal delay time. Thus more scatter should be expected with longer in-the-hole delays, indicating that in the case of pyrotechnic detonators precise timing is impossible. Whether precise timing is needed is still debated. However in the case of presplitting and vibrations, precision of firing times has shown distinct advantages.

Figure 2 shows the VOD record in the case in which two decks of AN/FO in a 160mm diameter borehole designed to detonate at different times, detonate sympathetically. It is obvious that the stemming distance in this case was insufficient to eliminate sympathetic detonations. VOD records reveal significant information in the case of sympathetic detonation or desensitization. While in the case of Figure 2 the VOD of the acceptor is similar to that to the donor, typically sympathetic detonations result in smaller energy yield. Figure 3 shows a typical record from a charge that detonated sympathetically. The proper Velocity of Detonation for this charge is 5500m/s. Table 2 presents results from tests conducted in granite in the case of 100mm diameter holes and decked emulsion explosives. The explosive

TABLE 2. Experimental Results for Decked Charges Containing Primers and Detonators

Separation Distance, cm	Donor VOD, m/s	Acceptor VOD, m/s	Timing of Acceptor Detonation, ms	Notes
100	4790	2040	1.25	
200	5400	4460	1.92	
160	5400	-	1.6	primer as acceptor
150	-	3700	3.45	
200	-	2210	18.1	Fractured hole
200	-	2033	3.5	
250	-	5400	5.21	
155	-	-	4.75	primer as acceptor
150	-	3310	21.2	Fractured hole
150		3280	2.3	
320	-		10.4	primer as acceptor

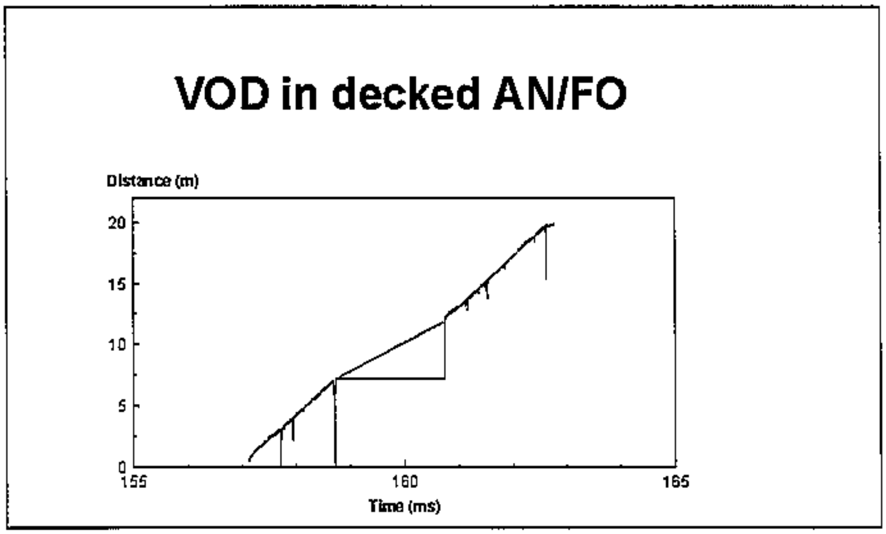

Figure 2: Sympathetic Detonation in the Case of Decked AN/FO charges.

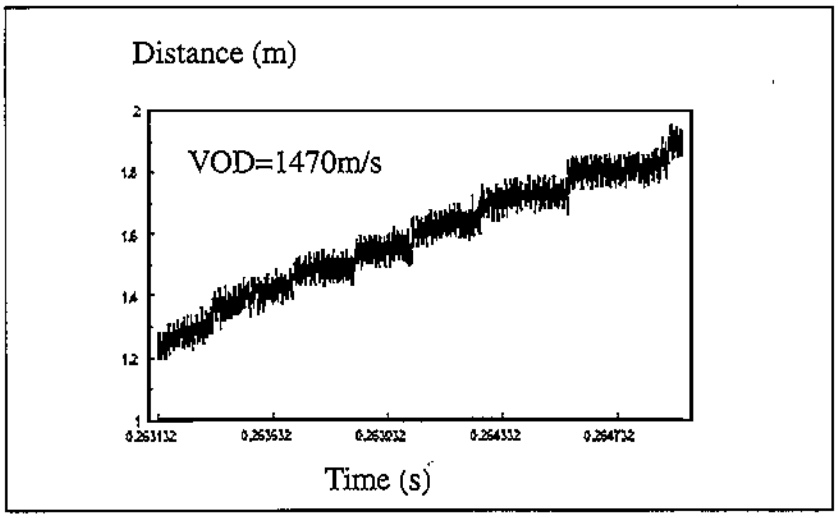

Figure 3: VOD Record for a Sympathetic Detonation

decks had a designed delay difference of 25ms and the stemming used was crushed rock. It is worth noting that the VOD of the "acceptor" is significantly reduced in most cases. In the case of a normal blasting application, this would have resulted in insufficient fragmentation and possibly increased vibrations. Without the revealing information obtained through continuous VOD measurement, the cause of bad blasting results caused by sympathetic detonations cannot be readily identified. Furthermore the timing of detonation is interesting suggesting that detonator malfunction may have been the case in some of these experiments.

VOD measurements have also allowed the examination of the effect of the stemming type on the sympathetic detonation problem. Figure 4 shows the results obtained in 100mm diameter schedule 40 steel pipes with a typical dynamite as the test explosive. Apparently sand or drill cuttings are not suitable as stemming materials while crushed rock is. It appears that bridging of the stemming material is of paramount importance in the case of sympathetic detonation.

The role of field conditions cannot be overemphasized when investigating explosive properties. Especially in the case of sympathetic detonations, field conditions change the role of confinement, which cannot be duplicated by steel in a laboratory set-up. Figure 5 shows the findings of VOD monitoring in 100mm and 160mm diameter boreholes using the explosive of Figure 4 and commercial emulsions and slurries. It is obvious that gap distances are much larger in the boreholes than in steel tubes.

It has been found that the only consistent method to examine whether sympathetic detonations, or generally malfunction, occur in boreholes, is measurement of detonation parameters. The fact that remnants, noxious fumes or large amplitude vibrations are not necessary outcome of a malfunction, makes investigation of in-the-hole performance the only valid method.

3.0 PRESSURE

Detonation pressure is typically measured in the laboratory using aquarium experiments. The description of these experiments falls beyond the purpose of this paper; however according to the experience of the author these tests require a significant investment without necessarily yielding superior infor-

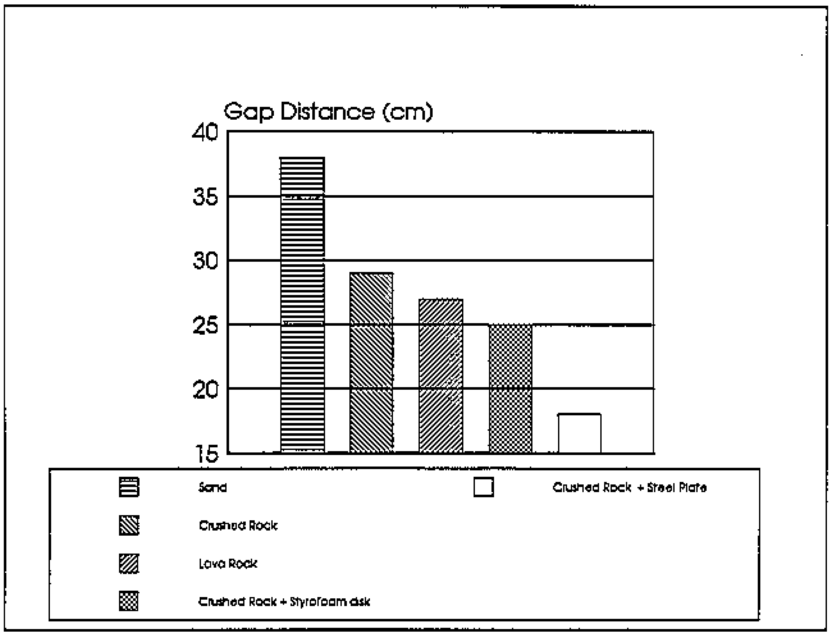

Figure 4: Gap Distances in Gap Tests in Steel Pipes with diameter of 100mm.

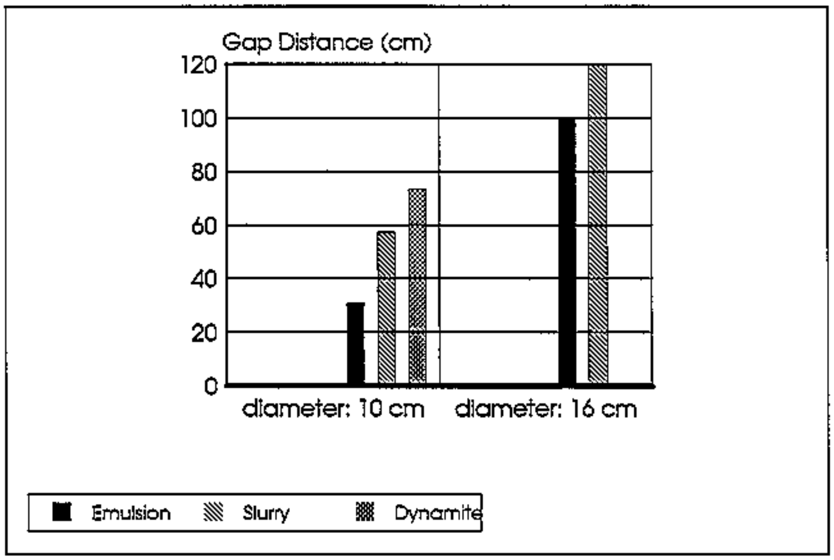

Figure 5: Critical Gap Distances in Boreholes.

mation to that obtained by the VOD value and equation (1). PVDF and manganin gauges have been also used in laboratory arrangements. While efforts are being undertaken to develop PVDF gauges for field use, it is also debatable whether the information obtained cannot be derived from equation (1). What is however needed is data on the shock attenuation in the rock mass and in stemming materials. Such data are of importance for placing explosive charges at proper distances so that malfunction is avoided and in order to understand the fragmentation process.

Dynamic pressure measurement is however a difficult task requiring expensive transducers. Piezoelectric or piezoresistive transducers have been used to measure pressure in one dimensional flow in homogeneous materials. However these techniques are not suitable for measurements in boreholes where the flow is not one dimensional and localized particle velocity gradients can damage the gauge before any useful information is obtained. Furthermore the destructive nature of the tests close to detonating explosives makes the operation costly. For this reason Wieland(1,2), Ginsberg and Asay(3) and the author(4) have used inexpensive carbon composition resistors to measure shock pressures with amplitudes up to 2.5 GPa (25000 bar).

In the case of carbon resistors the parameter which is measured is the resistance of the gauge as a function of pressure. Since the relationship is not linear a calibration of the system is necessary. The experimental set up for a typical high pressure calibration is shown in Figure 6. The voltage recorded is converted into resistance change which in turn is converted to pressure. Typical equations, such as those proposed by Ginsberg and Asay(3) for pressures above 0.1 GPa (1kbar) and Wieland for pressures below 0.1 GPa, making the resistance to pressure are then employed or derived.

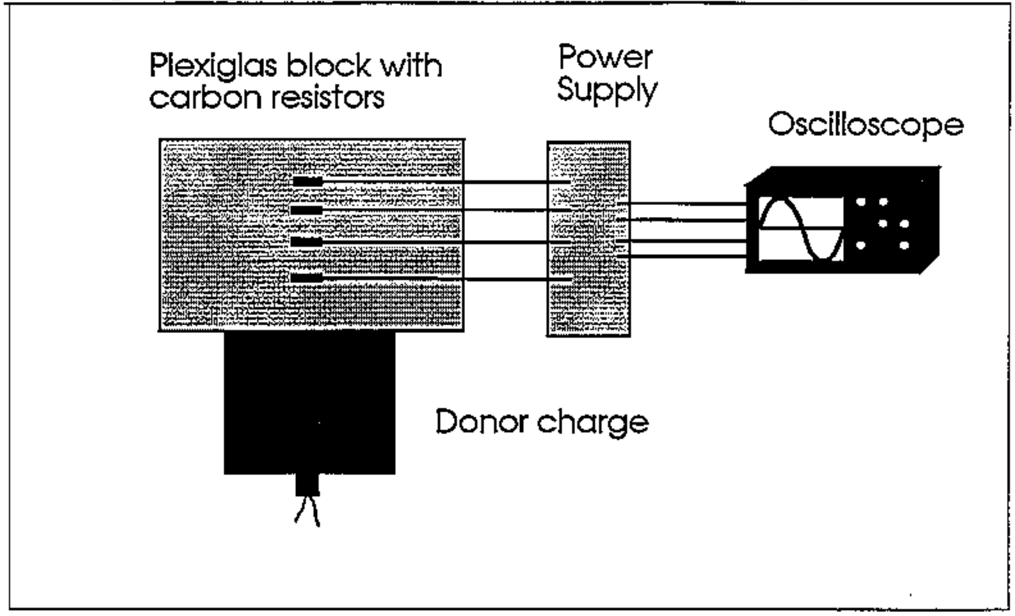

Figure 6: Calibration of Carbon Resistors for Pressure Measurements

In the case of the calibration of our system, the equations from Ginsberg, Asay and Wieland, converting the resistance measurements into pressures, were compared against the results obtained from the optical calibration of the same test using the measured shock wave velocities(4) from the streak camera measurements. As shown in Figure 7(4) the results were not only repeatable but accurate up to a pressure of 2.5 GPa. Above this pressure the accuracy of the measurement is lost due to the very small resistance of the carbon gauges at high pressures.

The success of the method resulted in application of the same method in the borehole. The carbon resistors were covered by epoxy glue, the connections were insulated and the gauges were placed in the stemming in the same borehole as the detonating explosive. The explosives used were the emulsion and slurry explosives of the borehole tests. The length of the charge used was 44 cm and its

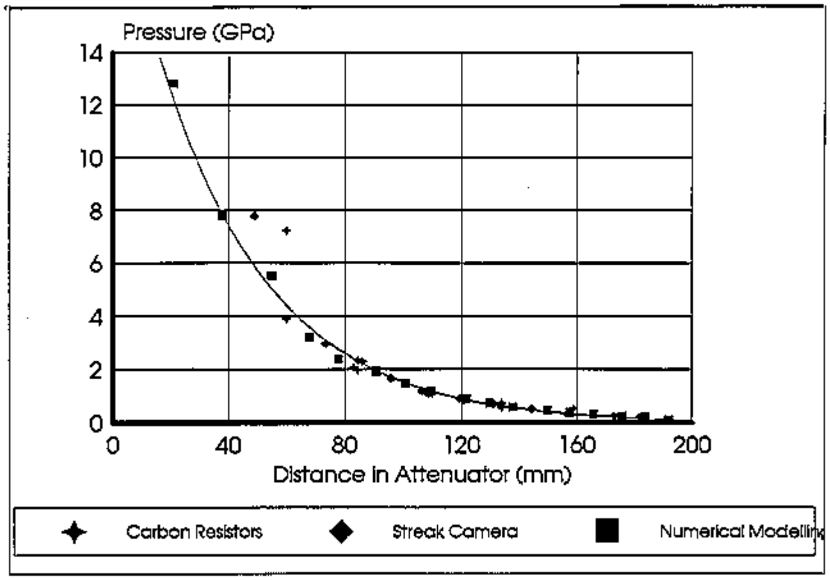

Figure 7: Comparison Between Pressure Measurements with Carbon Resistors Streak Camera and Numerical Modelling Calculations.

diameter was 10 cm. The boreholes in these experiments were wet. The results for two explosives tested in 100 mm diameter boreholes are shown in Table 3.

TABLE 3. Pressure Measurements in Boreholes

	Pressure (GPa)	
Distance from Donor, cm	**Emulsion Donor**	**Slurry Donor**
10	>2.5	-
25	0.61	0.46
40	0.4	0.44
60	0.35	0.4
100	0.19	0.37
150	0.12	-
200	0.10	-

It appears that shock waves maintain a significant amplitude away from the donor charge. Attenuation is rapid initially but its rate slows down at longer distances. As a result, pressures of the order of 0.1 GPa (1kbar) could be observed even at a distance of 2 m away from the explosive charge. This is significant and although it may be below the critical pressure to shock initiate commercial explosives, it is probably sufficient to start an ignition process or result in desensitization. This is obvious if one correlates Table 3 with Table 2 realizing that measurements were taken under practically the same conditions. In every case the practical result would be energy yield below expectation.

The author(5) has conducted laboratory measurements to examine the effect of pressure on explosives and detonators. It was found that desensitization of cap sensitive emulsion occurs at pressures above 13 MPa (130 bar). At a pressure of 27 MPa (270 bar) the desensitization is rather complete. Similar pressures have been found to affect timing and performance of pyrotechnic detonators.

These observations were made in the case of 32 mm diameter charges. Although there is reason to believe that pressure is the main reason for desensitization, energy delivered must be investigated. Obviously this is not of practical value for the blasting engineer whose concern is to use proper separation distances at the conditions of the blast design. In this case, diameter of the charge, characteristics of the rock mass and/or the attenuating medium and the nature of the explosive used, would be of importance. The author believes that there is enough laboratory information which can be interpreted to yield practical results. It is expected that such results, providing practical guidelines, should become available in the near future.

4.0 ENERGY

Several methods exist for the measurement of the energy from commercial explosives, These methods include mostly indirect methods like TNT equivalence tests, ballistic mortar and underwater bubble tests. It is not clear which method provides a good measure of the energy of detonation since energy losses in various forms cannot be accounted for.

The only direct method of energy measurement is the calorimetric determination. However this requires a detonation calorimeter which is not readily available to most laboratories as well as the ability to detonate the explosives in small enough diameters (approximately 12-13mm). Obviously very few commercial explosives can detonate under these conditions and all of them would detonate non ideally. Previous work by the author(6) has however demonstrated that commercial explosives can be sensitized to achieve detonation in small diameters and non-ideal detonation does not inhibit the measurement as long as the explosive is fully consumed in the detonation and the reactions that occur in the expansion zone.

Nevertheless the above methods require sophisticated equipment and/or a significant amount of analysis in order to yield a result that can be meaningful to blasting engineers. It is for this reason that in many cases energy values are calculated using thermodynamic codes.

There is no question that the term “energy” is well understood; the values obtained by the commonly used indirect tests need however interpretation for field use. Energy is also partitioned during the blasting process into shock and heave components. This partition considers both the explosive and the rock type. Generally, explosives with high VOD offer more shock and explosives with the same total energy, but low VOD, offer less shock, but more heave energy.

The average user will however be confused with the term energy when “strength” is implied. There are many formulae calculating strength which make comparison of different products almost impossible. It is the experience of the author that in terms of energy there is only one correct value; the value measured in a direct calorimetric experiment or predicted by codes when the calculated composition of the product gases is correct. The partition and use of this energy is a matter of the interaction between explosive and rock and has to be considered before blast patterns can be modified.

5.0 CONCLUSION

Velocity of Detonation measurements offer information on performance of explosives under practical conditions. Such information is important to evaluate not only performance but malfunction such as sympathetic detonation and desensitization.

Pressure measurements are important in understanding attenuation of waves in the rock or in the stemming. Inexpensive carbon resistors can provide significant information since they can measure pressures from few bar to 25,000 bar.

Energy measurements need interpretation in order to be applied in blast design. Because of the variety of methods of calculation, the "heat of reaction" and its partition in a specific blasting application should be used.

6.0 REFERENCES

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