Comparison of the Non-Ideal Shock Energies of Sensitised and Unsensitised Bulk ANFO-Emulsion Blends in Intermediate Blasthole Diameters

K.G. Fleetwood*, E. Villaescusa*, J. Eloranta**
**Western Australian School of Mines/CRC Mining*
***Eloranta & Associates Inc.*

ABSTRACT

The work presented in this paper investigates the influence of non-ideal detonation characteristics related to the blasthole diameter, base emulsion sensitivity (micro-balloon sensitised versus unsensitised) and percent emulsion on the explosive shock energy available to break rock using ANFO-emulsion blends. A series of theoretical equal powder factor bench blasting patterns with hole diameters of 127mm (5”), 140mm (5.5”), 152mm (6”) and 165mm (6.5”) are compared to assess the non-ideal confined shock-state work energies. The Non-Ideal Shock Energy Factor (NSEF), which is the available shock energy per cubic meter of blasted material (MJ/m^3) or kilocalories per cubic yard ($kcal/yd^3$), is used to compare the different blasting patterns charged with a range of ANFO-emulsion blends from zero to 50% emulsion.

Initial results based on modified analysis of historical explosives testing data indicate that the relationship between percent emulsion (blend density) and NSEF for unsensitised emulsion blends is opposite to that expected from ideal detonation modelling. The data from sensitised emulsion blends is more consistent with what would be expected. For intermediate hole diameters (> 102mm, 4”) or at higher emulsion percentages (> 30%), the detonation behaviour of sensitised emulsion blends far exceeds that of unsensitised blends according to the data. The example unsensitised emulsion blend at greater than 20% emulsion produced velocities of detonation (VODs) up to 50% less than the same percent blend using the example micro-balloon sensitised emulsion. This indication suggests that the difference between the detonation performances of unsensitised versus sensitised emulsion blends increases with percent emulsion. This is an important factor when comparing the costs and benefits of sensitised and unsensitised emulsions used in blends of 20-50% in intermediate blasthole diameters typical of quarry blasting or small-scale open pit blasting.

1. INTRODUCTION

Finer fragmentation resulting from smaller blasthole diameters and tighter patterns is typically required in quarry blasting or smaller-scale open pit metal mining due to lower-capacity loading and haulage equipment and smaller primary crushers. Other factors contributing to the need for decreased hole diameters are mining selectivity (separation of narrow, high-grade ore zones from waste or selection of better quality stone) and environmental controls on ground vibration, air overpressure or fume production. These restrictions, coupled with an attempt to achieve economies of scale in drilling and blasting programs, has lead to widespread use of intermediate blasthole diameters ranging from 127 to 165mm (5.0 – 6.5”) in larger-scale quarrying and small-scale, selective open pit mining.

The number of available explosive products, product mixes and delivery systems for intermediate hole diameters is several times greater than that for smaller hole diameters of 52-102mm (2-4”) [e.g. stick and bag loading] or larger diameters in excess of 200mm (8”) [large-capacity bulk delivery]. For hole diameters between 127 and 165mm (5-6.5”) the possible product mixes include: 100% bulk products (bulk ANFO, emulsion or blends), 100% packaged products (wet bags and bagged ANFO) or a mix between the two (e.g. wet bags and bulk ANFO). The decision as to which delivery system and product mix is most suitable is a function of operational, logistical, topographic and economic factors. Frequent, smaller blasts of intermediate hole diameters with only occasional water using might prompt the use of packaged wet-hole product (bagged emulsion), coupled with either bulk or bagged ANFO. Larger blasts of varying water conditions would suggest the use of either pumped bulk emulsions or auger-delivered ANFO-emulsion blends (heavy ANFO, HANFO) capable of loading over a range of emulsion percentages to increase explosive energy and water resistance. The capability of delivering either blends or ANFO from the same mobile manufacturing unit (MMU) allows the practice of loading the toes of blastholes (approximately 25-30% of the column length) with an ANFO-emulsion blend and the remaining column with only ANFO. Common blend percentages for toe loading applications in quarry blasting is 25-40% emulsion, and full-column blend charging in open pits is approximately 40-50% emulsion blends.

Once a bulk ANFO-emulsion blend is selected as the most appropriate blasting agent, the method of emulsion sensitisation must be decided upon. Traditionally, unsensitised emulsion is cheaper than glass micro-balloon (GMB) sensitised or chemically-sensitised emulsions, which has added to the popularity of using unsensitised emulsion matrices in “light” blends (20-30% emulsion). The detonation characteristics of unsensitised emulsions in blends are not well understood by the end explosives users (and arguably the field representatives for the manufacturers) and thus should be investigated further.

The results of in situ or unconfined velocity of detonation (VOD) measurements of sensitised and unsensitised ANFO-emulsion blends in intermediate charge diameters are not extensively published in the literature or explosive product data sheets. The general belief amongst field users and field support staff (speaking from the primary author’s experience) is that the detonation characteristics of unsensitised blends are consistent with sensitised blends up to an emulsion percentage of approximately 30%, after which unsensitised blends should not be used due to a lack of detonation sensitivity. Data published by Bauer et al. (1984), comparing the VODs of sensitised and unsensitised emulsion blends over a range of charge diameters clearly indicate that this behaviour is not realistic and that virtually any percentage unsensitised emulsion in a blend can reduce the unconfined or confined VODs relative to similar sensitised products.

2. INFLUENCE OF BOREHOLE DIAMETER AND BLEND EMULSION PERCENTAGE ON VOD

It is generally accepted that the VOD of a commercial bulk blasting agent increases with increasing borehole diameter or increasing density (up to a critical density, where failure occurs). It is also generally accepted that the sensitivity of an explosive to charge diameter, indicated by the decrease in VOD with decrease in charge diameter, is a function of the degree of non-ideality. ANFO is generally viewed as an explosive of low ideality and emulsion of higher ideality. ANFO-emulsion blends behave somewhere between, depending on the percent emulsion and the degree and type of sensitisation of the emulsion matrix.

2.1. Sensitised and Unsensitised ANFO-Emulsion Blends

Field data on the measured velocities of detonation of sensitised and unsensitised emulsion blends as functions of blend density (or percent emulsion), charge diameter and confinement characteristics are limited in the published literature. The data set of Bauer et al. (1984) has therefore been used to compare the steel pipe-confined VODs of an ANFO-emulsion blend containing a glass micro-balloon sensitised emulsion (1.6% GMB by weight) and a blend containing the same emulsion matrix unsensitised. The range in percent emulsions is 0-50% and charge diameters of 50mm (1.9”) to 250mm (9.8”). The data published by Bauer et al. (1984) and the general trends for charge diameters between 50 and 250mm (2” and 9.8”) are shown relative to ANFO in Figure 1.

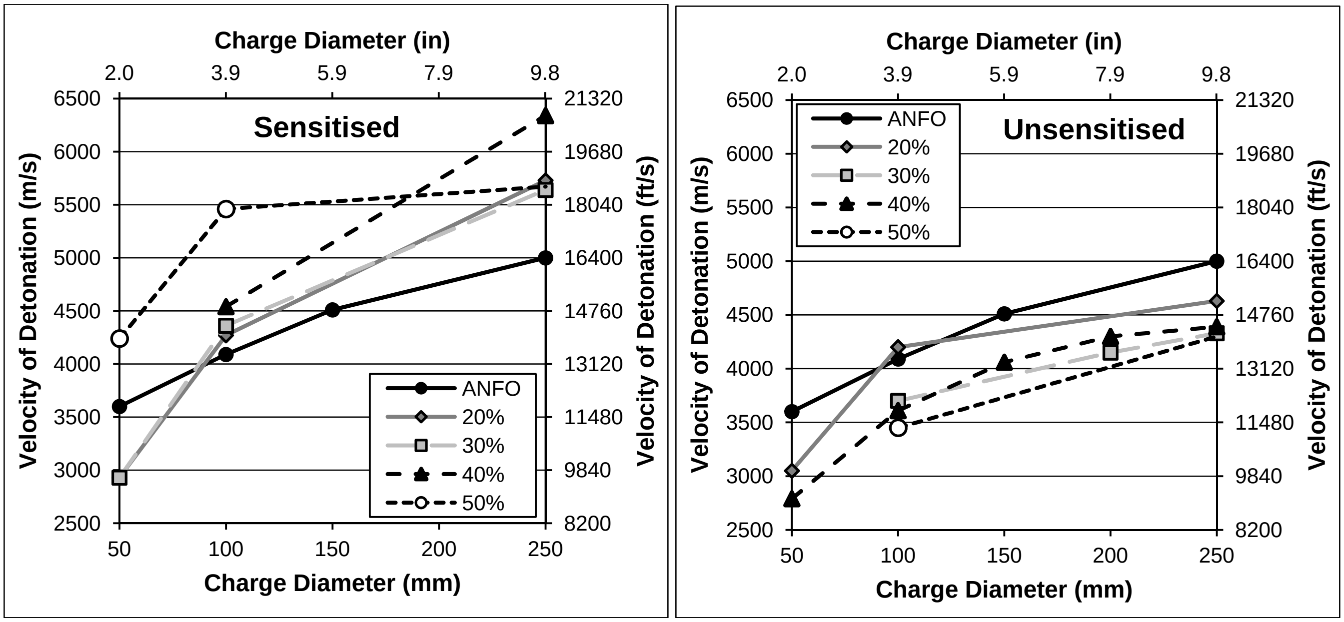

Figure 1. Velocity of Detonation (VOD) data for steel-confined pipe tests of glass micro-balloon (GMB) sensitised (left) and unsensitised (right) emulsion-ANFO blends (after Bauer et al., 1984).

The data in Figure 1 clearly indicates different relationships between the measured VODs and percent emulsions for the sensitised and unsensitised blends relative to plain ANFO. The data of the sensitised emulsion blends are close to what would be expected, with increasing VODs observed for higher percent emulsion blends. The data for the unsensitised emulsion blends is opposite to that of the sensitised blends, suggesting a loss of performance relative to ANFO for increased emulsion percentages. The VODs for the unsensitised blends of the most common blend percentages (between 30% and 50% emulsion) were up to 15% lower than plain ANFO and up to 37% lower than the sensitised blend over the range in diameters. The data point for the 250mm (9.8”) 40% sensitised emulsion (Figure 1, left) is questionably high, as the test results for both 45% and 50% emulsions at 250mm were approximately equal at 5700 m/s (18695 ft/s).

The increase or decrease in measured sensitised or unsensitised blend VODs relative to ANFO was investigate further by plotting the VOD value for each emulsion percentage (ψ) for a single diameter.

The only two diameters available around the target intermediate diameter range were 100mm (4”) and 250mm (9.8”). The data for both these diameters is shown in Figure 2.

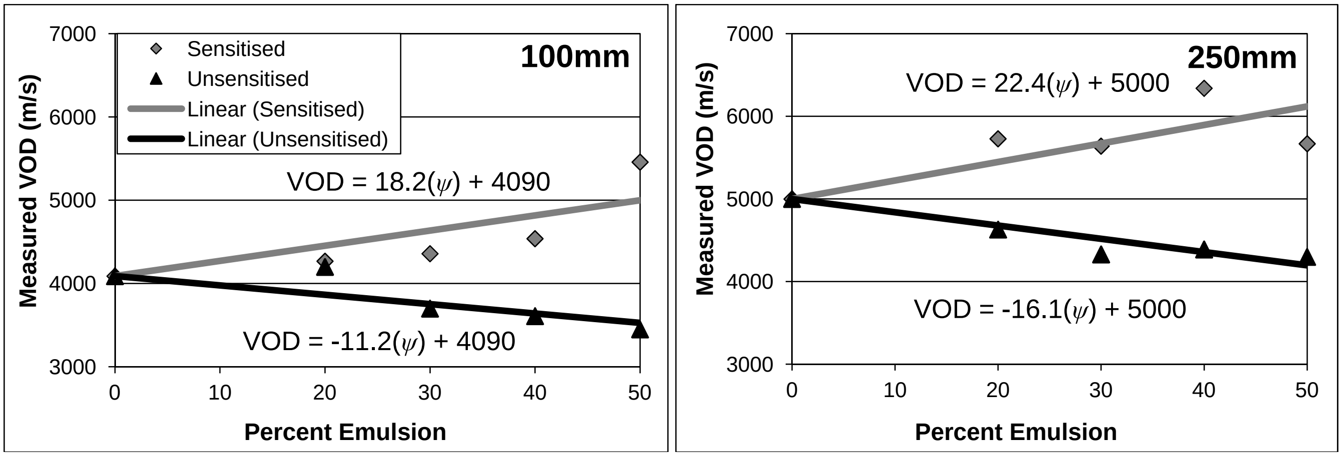

Figure 2. Measured VOD values for steel pipe confined tests of sensitised and unsensitised emulsion-ANFO blends in 100mm (4”) (left) and 250mm (9.8”) (right) diameters.

The observed differences between the sensitised and unsensitised emulsion blend VODs should be considered when selecting a suitable emulsion for a blended product, especially in intermediate hole diameters where increased sensitivity may be required due to wet holes, long sleep times or poor product quality from repeated cycling or excessive storage times. The more non-ideal detonation characteristics of the unsensitised blends are not accurately represented by ideal detonation modelling, as the chemical energy contained within the two emulsions would be virtually identical and thus a non-ideal consideration is required.

2.2. Empirical Relationship Between Blend Emulsion Percentage, Charge Diameter and VOD

A number of researchers have published approaches to define the shape of the diameter sensitivity of various blasting agents in both small and large charge diameters (e.g. Sun et al., 2001 and Esen, 2004). These proposed two-dimensional empirical models are useful to characterise the relationship between the charge diameter and a single explosive product at a single density, but have not described the multi-dimensional relationship between emulsion density or blend percentage, charge diameter and VOD. The first published attempt at characterising the three-dimensional surface relating the VOD with the density and diameter for pure chemically-sensitised emulsions was published by the authors (Fleetwood and Villaescusa, 2011). This model has been further expanded and modified to consider ANFO-emulsion blends.

A relationship describing the dependence of the ideal VOD at infinite diameter (VOD_{CJ}) and subsequent measured VOD on blend percentage and diameter simultaneously has been proposed by analysing the example data of Bauer et al. (1984). Two different relationships were required to represent the proposed three-dimensional VOD surface and to determine the contribution of both charge diameter and emulsion percentage on the measured VOD values. The first relationship required was that between the percent emulsion and the VOD at a constant diameter. The data suggested that VOD increased (sensitised emulsion) or decreased (unsensitised emulsion) nearly linearly with increasing percent emulsion relative to ANFO (Figure 2). The second required relationship was that between VOD and diameter at a single percent emulsion. This relationship was identified as roughly exponential in shape (Figure 1), with a horizontal asymptote at the VOD_{CJ} and a vertical asymptote at the critical diameter (ϕ_{crit}). The linear and exponential relationships were then combined to describe the general form of the three-dimensional VOD surface as a function of percent emulsion and diameter (Equation 1).

$$VOD = \left(A \cdot \psi + VOD_{CJ(ANFO)}\right) \cdot \left(1 - exp\left(- B \cdot \left(\phi - \phi_{crit}\right)\right)\right) + C \tag{1}$$

Where VOD = velocity of detonation for blend (m/s)
ψ = percent emulsion in blend (%, e.g. 20, 30, etc)
$VOD_{CJ(ANFO)}$ = $\mathrm{VOD_{CJ}}$ of ANFO (m/s)
ϕ = borehole diameter (mm)
ϕ_{crit} = critical diameter (mm)
A, B, C = fitting parameters

The term ($A \cdot \psi + VOD_{CJ(ANFO)}$) represents the VOD_{CJ} of the emulsion blend as a function of the percent emulsion in the blend. The individual VOD_{CJ} values for each percent emulsion are the horizontal asymptotes of the exponential diameter-VOD plots (for example Figure 1). The values obtained for the constants A, B and C from nonlinear multi-variable regression of the data of Bauer et al. (1984) are listed in Table 1. The values of ϕ_{crit} for the different blends were not specified and as such were not included in the regressed relationships.

Table 1. Regression constants from nonlinear multi-variable regression of Equation 1 using the data of Bauer et al. (1984).

Regression Constant	Unsensitised Emulsion (R = 0.95)	Sensitised Emulsion (R = 0.93)
A	-16.4	20.8
B	0.022	0.018
C	-185.7	-14.8

The form of Equation 1 represents a three-dimensional surface defined by the independent axes of diameter and percent emulsion and the dependent value of VOD. The data used in the regression of the sensitised and unsensitised emulsion blends and the surfaces defined by the regression constants listed in Table 1 have been plotted in Figure 3 to display the relationship between the percent emulsion, charge diameter and steel-confined VOD in both sensitised (left) and unsensitised (right) emulsion blends.

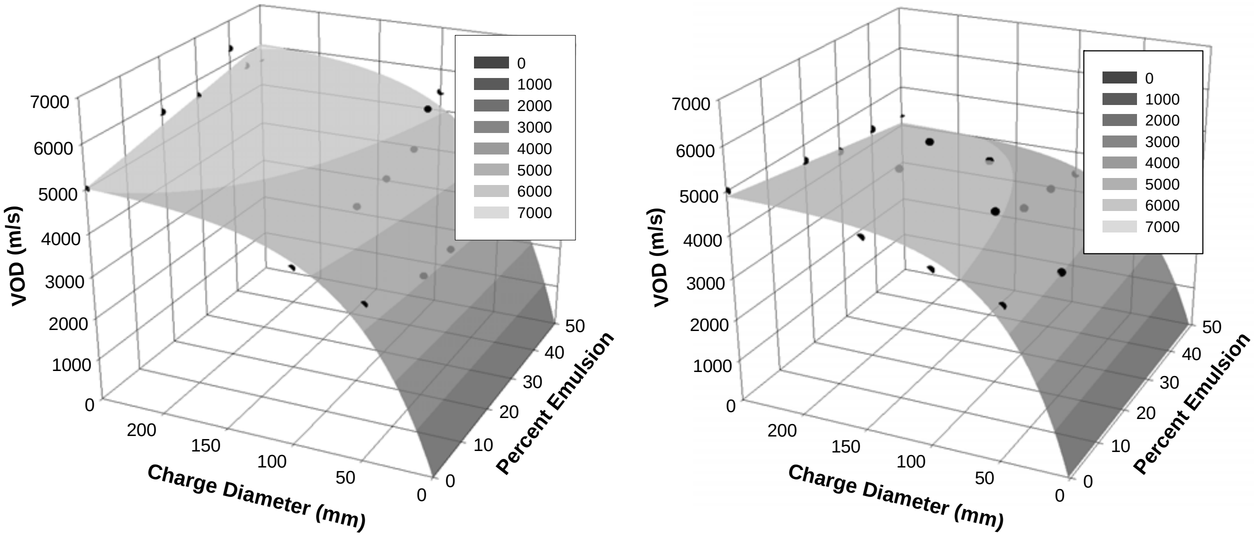

Figure 3. Data points of Bauer et al. (1984) and the three-dimensional surfaces defined by Equation 1 and the regression constants in Table 1 for the sensitised (left) and unsensitised (right) emulsion blends.

Equation 1 and the regression constants in Table 1 have been used to estimate the highly-confined VODs of the example sensitised and unsensitised emulsion blends from 0 to 50% emulsion over the range of intermediate blasthole diameters included in this study. Table 2 lists the resulting estimated VOD values at a charge diameter of 152mm (6”).

Table 2. Estimated steel-confined VOD values for unsensitised and sensitised emulsion-ANFO blends at 152mm (6”) diameter.

Percentage Emulsion (%)	Unsensitised Blend VOD (m/s)	(ft/s)	Sensitised Emulsion VOD (m/s)	(ft/s)	Ratio Sens/Unsens VOD
0	4725	15500	4745	15565	1.00
20	4410	14465	5135	16845	1.16
30	4250	13940	5330	17480	1.25
40	4090	13415	5525	18120	1.35
50	3935	12905	5720	18760	1.45

The values in Table 2 suggest that the highly-confined VOD of the unsensitised emulsion blend is up to 1.5 times lower than that of sensitised emulsion blend at a diameter of 152mm (6”). This relative reduction in VOD for the unsensitised emulsion blend would be expected to significantly reduce the detonation pressure and subsequent energy available to perform breakage and movement when compared with the sensitised blend. At lower emulsion percentages (< 25%), the relative VOD difference between the two emulsion matrices would be somewhat insignificant. For the most common blend percentage used in toe loading of intermediate hole diameters in quarry blasting and small open pits (~30%), the estimated VOD could be reduced by up to 20% in comparison. For the heavy blends between 40 and 50% emulsion, the reduction in unsensitised VOD relative to the sensitised blend was over 30% according to the analysis results and the published data.

3. NON-IDEAL VELOCITIES OF DETONATION AS A RESULT OF CONFINEMENT

The increase in VOD of commercial explosive products as a function of increased confinement has been observed by many past researchers from the results of steel pipe tests and in situ field measurements. Esen (2008) suggested an empirical relationship between the degree of charge confinement and the VOD of different explosive formulations as a function of the unconfined (VOD_u) and ideal (VOD_{CJ}) explosive VODs and the ratio of the shock impedances of the explosive and rock. The empirical relationship is provided in Equation 2.

$$VOD_c = VOD_u\left(1+\left(\frac{VOD_{CJ}-VOD_u}{VOD_{CJ}}\right)\left(\frac{M}{1+\left(4.563\cdot M^{0.688}\right)}\right)\right) \tag{2}$$

And

$$M = \frac{\rho_r \cdot V_p}{\rho_0 \cdot VOD_u}$$

Where VOD_c = confined explosive VOD at given borehole diameter (km/s)
VOD_u = unconfined explosive VOD at given borehole diameter (km/s)
VOD_{CJ} = ideal VOD (km/s)
ρ_r = rock density (g/cm^3)
V_p = P-wave velocity of rock (km/s)
ρ_0 = initial explosive density (g/cm^3)

The term M in Equation 3 refers to the ratio of the specific acoustic impedance of the confining medium to the shock impedance of the explosive. This ratio influences the transmission of pressure and thus energy across the borehole wall (Cooper, 1996). Equation 2 has been used to estimate both the unconfined VOD (VOD_U) of the various emulsion blends using the confined values from the steel-pipe tests of Bauer et al. (1984), where the M values was calculated using ρ_{steel} = 7.85 g/cm^3, and $V_{p(steel)}$ = 6.1 km/s. The unconfined values were then used to calculate the limestone-confined values, discussed further in Section 6.

4. APPROXIMATE AVAILABLE SHOCK ENERGY CONTENT OF THE ANFO-EMULSION BLENDS IN THE BOREHOLE

The detonation pressure and the subsequent explosive shock energy or hydrodynamic work at the low-expansion state for an explosive can be estimated using the explosive VOD. A commonly used equation for calculating the detonation pressure (PD) of an explosive from the unreacted explosive density and velocity of detonation is given in Equation 3 (Cooper, 1996).

$$PD = \frac{\rho_e \times VOD^2}{\gamma + 1} \tag{3}$$

Where PD = detonation pressure (GPa)
VOD = velocity of detonation (km/s)
ρ_e = explosive density (g/cm^3)
γ = ratio of specific heats of detonation product gases ($\gamma \approx 3$)

One assumption when using Equation 3 is that the value of γ is constant and approximately equal to three. During the detonation process, γ decays as the expansion state relative to the CJ state increases, but at the peak pressure (shock state with low expansion) γ may be approximately 2.6 for ANFO to 3.2 for emulsion (Cunningham, 2002). These values represent an approximate ±10% range around the assumed value ($\gamma \approx 3$) and therefore the assumption appears to be acceptable for the shock state and well within the range of measurement error for other values such as VOD.

It is proposed that the detonation pressure calculated from Equation 3 can be used to approximate the shock energy content of the explosive using Equation 4. Equation 4 is a modification of the hydrodynamic work function provided by Cooper (1996), which is typically applied to high explosives (near ideal detonation). This approach would therefore be expected to provide a poor approximation of the total energy content of non-ideal blasting agents that contain significant gas energy, but may be a justifiable approximation for comparison of shock energies of different explosives. More accurate values would be provided by non-ideal detonation codes considering the individual equations of state of the detonation products, but these modelling tools are not readily available to explosives users and therefore a method of approximation and comparison becomes useful.

$$E_{expl} = \frac{X \cdot PD}{\rho_{CJ}} \tag{4}$$

And

$$\rho_{CJ} \approx \frac{4}{3}\rho_e$$

Where E_{expl} = useful shock energy content per unit mass (MJ/kg)
X = ratio of chemical energy converted into useful work energy
PD = detonation pressure (GPa)
ρ_{CJ} = density of explosive at CJ plane (g/cm^3)
ρ_e = unreacted explosive density (g/cm^3)

4.1. Useful Work Energy Available to Perform Breakage and Material Movement

The conversion of potential chemical energy of an explosive into useful energy or work in unconfined or lightly confined conditions depends on the explosive type, the efficiency of the chemical reaction between the oxidiser and fuel components and the oxygen balance. More ideal explosive formulations such as emulsions typically convert a higher percentage of chemical energy into high pressure gases than less ideal explosives such as ANFO. This conversion efficiency is related to the amount of useful work an explosive can perform during rock blasting. One useful method of examining the available work energy of an explosive is through cylinder testing for determination of Gurney energies. Gurney ratios, which represent the percentage of available chemical energy converted into expansion energy during cylinder tests would not be expected to reliably represent in situ borehole conditions, but does provide a method of comparison between different explosive formulations in absence of dedicated detonation modelling. Some researchers suggest that cylinder testing provides the most accurate test-derived indication of potential energy transfer from an explosive to a rock mass (Esen et al., 2005).

Gurney energies for ANFO and bulk emulsions have been investigated by Nyberg et al. (2003) using cylinder expansion tests of large-diameter samples. The testing results identified Gurney energies of 40-56% for various ANFO products and 46-74% for Titan 6000 and 6080 gassed bulk emulsions. These values were comparable to values published by López et al. (2002) for watergel slurry and ANFO, which were 73.2% and 66.5%, respectively, based on the heats of reaction. The work of Nyberg et al. (2003) also suggested that the conversion of chemical energy to useful work in bulk emulsions had a strong dependence on the emulsion density. This theory was therefore applied to the blend data of Bauer et al. (1984) to estimate the Gurney ratios (X value in Equation 4) for each emulsion type and percent blend. The linear relationship between the emulsion density and the Gurney ratio published by Fleetwood and Villaescusa (2011) was adapted to the sensitised and unsensitised blends to determine the X value for each blend percentage. The value at 0% sensitised emulsion was assumed to be that of ANFO ($X = 0.5$), and increased linearly to $X = 0.6$ at 50% emulsion; X decreased linearly from 0.5 (0%) to 0.4 at 50% for the unsensitised blend. The decreasing Gurney ratios for the unsensitised blends were proposed from observations of the lower VOD values and thus decrease in ideal behaviour with increasing unsensitised blend emulsion percentage. The functions suggested for predicting the Gurney ratio for the unsensitised and sensitised blends as a function of density (ρ_e in g/cm^3) were $X = 0.68-0.21\rho_e$ and $X = 0.20+0.37\rho_e$, respectively

5. COMPARISONS OF CONFINED VODS AND AVAILABLE EXPLOSIVE WORK OF UNSENSITISED AND SENSITISED EMULSION BLENDS IN LIMESTONE

The non-ideal, limestone-confined VODs, Gurney ratios and available shock energies of the unsensitised and sensitised emulsion blends were compared for a given rock type over a range of emulsion percentages using Equations 1 to 4. A dense limestone, common to intermediate hole diameter quarry blasting was selected for the comparison. The physical properties of the limestone required for the VOD calculations are listed below.

Rock Type: Limestone
$\rho_R = 2.55$ g/cm^3
$V_p = 4500$ m/s (14760 ft/s)

The results of the calculations of non-ideal, confined VODs and shock energies per kilogram of explosive in the limestone over the range in blend percentages for a 152mm (6”) blasthole are listed in Table 3.

Table 3. Predicted limestone-confined VOD and available work energy of unsensitised (Unsens) and sensitised (Sens) emulsion-ANFO blends in 152mm (6”) hole diameter.

Emuls %	VOD$_{C(Unsens)}$		Gurney Ratio$_{Unsens}$	Shock Energy$_{Unsens}$		VOD$_{C(Sens)}$		Gurney Ratio$_{Sens}$	Shock Energy$_{Sens}$	
	(m/s)	(ft/s)		(MJ/kg)	(kcal/lb)	(m/s)	(ft/s)		(MJ/kg)	(kcal/lb)
0	4620	15155	0.50	2.01	217.8	4650	15250	0.50	2.01	217.8
20	4315	14155	0.46	1.61	174.4	5070	16630	0.54	2.60	281.7
30	4160	13645	0.44	1.44	156.0	5240	17190	0.57	2.91	315.3
40	4005	13135	0.41	1.25	135.4	5380	17645	0.59	3.20	346.7
50	3850	12630	0.40	1.11	120.3	5590	18335	0.60	3.51	380.3

The divergent nature between the unsensitised and sensitised blend VODs with increasing emulsion percentage (as observed in Figure 2) is further compounded with calculation of the detonation pressures and subsequent available shock energies. The data in Table 3 suggests that the available shock energy for the sensitised, 50% emulsion blend is more than 3 times that of the unsensitised blend for a 152mm (6”) diameter in limestone. In addition, the available shock energy for the unsensitised emulsion is less than that of ANFO at the same diameter, even though the density is significantly higher. These changes in detonation characteristics with unsensitised emulsion would suggest that the increasing degree of non-ideality of the unsensitised blend would have a significant impact on the explosive performance within a blasting pattern.

6. COMPARISON OF NON-IDEAL ENERGY FACTORS FOR EQUAL POWDER FACTOR BLASTING PATTERNS IN LIMESTONE

The implications of the reduced in-hole VODs and available shock energies on the estimated blast performance for the sensitised and unsensitised ANFO-emulsion blends were further investigated by comparing a series of theoretical blasting patterns in limestone. The theoretical sensitivities of each product to blasthole diameter were also compared using four example, equal powder factor blasting patterns, charged with either sensitised or unsensitised emulsions of 30% emulsion blend. The four compared patterns were designed using existing rules of thumb for burden, spacing, subdrill and stemming length and representative bench heights used in quarry blasting. The reference design powder factor was 0.84 kg/m^3 (1.41 lb/yd^3) for the four intermediate hole diameters of 127-165mm (5-6.5”). The shock energy values were then used to calculate the Non-Ideal Shock Energy Factors (NSEF) for each theoretical pattern, as charged with HANFO blends containing 30% unsensitised or sensitised emulsion. The resulting pattern dimensions and NSEF values are listed in Table 4.

Table 4. Pattern dimensions and NSEF values calculated for equal powder factor blast patterns charged with either unsensitised or sensitised 30% emulsion blends in limestone.

Diameter		Burden		Spacing		Powder Factor		Unsensitised NSEF		Sensitised NSEF	
(mm)	(in)	(m)	(ft)	(m)	(ft)	(kg/m^3)	(lb/yd^3)	(MJ/m^3)	(kcal/yd^3)	(MJ/m^3)	(kcal/yd^3)
127	5.0	3.3	10.8	4.5	14.8	0.84	1.41	1.13	206.4	2.23	406.8
140	5.5	3.6	11.8	5.0	16.4	0.84	1.41	1.17	213.0	2.33	426.5
152	6.0	3.8	12.5	5.5	18.0	0.84	1.41	1.20	220.1	2.44	446.3
165	6.5	4.1	13.4	5.9	19.4	0.84	1.41	1.24	226.7	2.55	465.2

The values in Table 4 are shown in Figure 4 to illustrate the significant differences between the available fragmentation energies per blasted volume for the example sensitised and unsensitised ANFO-emulsion blends.

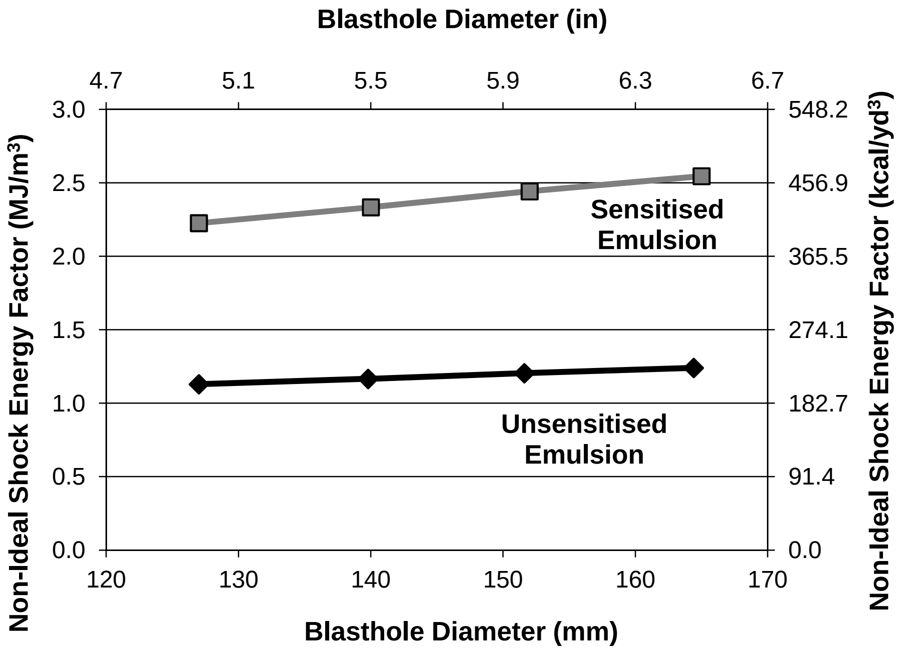

Figure 4. Plot of blasthole diameter and NSEF for 30% unsensitised and sensitised emulsion blends in equal powder factor patterns in limestone.

As observed in Figure 2, the NSEF values for the 30% unsensitised emulsion blend are approximately half of that for the sensitised emulsion blend in patterns of equal powder factor. The increase in available shock energy to perform rock breakage and would suggest that the pattern loaded with the sensitised emulsion would result in better fragmentation. The non-ideal shock energy factor could therefore be used in place of powder factor as a blast design parameter to assess probable blasting outcomes from different explosive products. Matching the NSEF values for both explosive products would require the pattern charged with the unsensitised emulsion blend to be reduced (or alternately spreading of the sensitised emulsion blend pattern) to achieve equal energy concentrations.

7. DISCUSSION AND CONCLUSIONS

The differences between the detonation characteristics of sensitised and unsensitised emulsion-ANFO blends of 0 to 50% emulsion in intermediate hole diameters have been investigated using the data published by Bauer et al. (1984). The unconfined and rock-confined VODs have been estimated from the measured steel-pipe confined VODs and used to calculate the available explosive shock energy perform rock breakage. These values have then been applied to theoretical limestone bench blasting patterns of equal powder factor to estimate the non-ideal shock energy factors over a range of intermediate blasthole diameters (127-165mm, 5-6.5”).

The analysis results suggest that the NEF values for the unsensitised emulsion blends were between two to three times lower than the sensitised emulsion blends over the range in blend percentages, with the greatest difference in NSEF values observed for the 50% blend. Also of importance were the differences between the 0% blend (straight ANFO) and the unsensitised blends of any percentage. The reduced

VOD and subsequent energy with increasing percentage unsensitised emulsion would suggest a loss in blast performance relative to ANFO at similar powder factors. Although the density of the unsensitised blend product was higher than ANFO, the increased density was not adequate to compensate for the increasing loss in VOD. This information is significant in dry blasting applications, where ANFO might be capable of producing a higher amount of explosive work than the unsensitised emulsion blend and therefore could represent more economic blasting. The cost savings of using unsensitised emulsions in blended products should therefore be weighed against the loss of performance relative to either ANFO or sensitised emulsion blends.

The non-ideal shock energy content of each blended product has been estimated using a proposed approach containing a number of key assumptions. These assumptions include a constant γ, use of the shock-state hydrodynamic work function to estimate the shock energy content and non-ideal behaviour described by the Gurney ratio from cylinder testing. These assumptions likely do not represent the realistic, confined detonation conditions in the field, but become necessary to estimate the detonation characteristics in the absence of non-ideal detonation codes or in situ measurements.

A new empirical equation has been proposed to describe the relationship between blend percentage, borehole diameter and non-ideal VOD (Equation 1). Except for previous work published by the authors (Fleetwood and Villaescusa, 2011), no such empirical relationships for emulsions or ANFO-emulsion blends have been discovered in the published literature. The observed decrease in VOD with increased percent unsensitised emulsion is not indicated by ideal detonation modelling, as indicated by Bauer et al. (1984). Therefore, the suggested relationships can aid in design of blasting operations where relative VOD values are required in cases of product selection (unsensitised or sensitised emulsion matrix for a blend, blend versus ANFO or blasthole diameter selection), or prediction of explosive performance. Due to the lack of published in situ VOD measurements for blends using different sensitising agents or different blend percentages, the proposed comparisons are based only on analysis of the data of Bauer et al. (1984). This lack of available data significantly restricts the use of the proposed regression constants listed in Table 1 for general use and therefore additional testing is required to better characterise the detonation behaviour of unsensitised and sensitised ANFO-emulsion blends for use in blasting applications.

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