DAMAGE AND COSTS ANTHOLOGY

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UNDERGROUND BLAST DAMAGE REVIEW - DEVELOPMENT

1.0 DAMAGE - DEFINITION & COSTS
1.1 DEFINITION OF DAMAGE

The JKMRC(1990) define damage as "any change in a material property which degrades the material's performance"

However, to operating mine personnel, the definition of damage has to have an economic or safety consequence for it to be of significance. Generally this will be in the form of overbreak or backbreak beyond the excavation limits for which the blast was designed.

The rock mechanics perception of damage to a rock mass is the reduction in rock mass properties such as Young's modulus of elasticity caused by an increase in the crack density of the rock mass, excessive displacement, yield or non-linear behaviour in the loading-deformation process - all of which imply a damaged rock mass. A mine operator in general will only be concerned about these aspects of damage if it has the potential to cause structural failure in the mine - be it pillar collapse, overbreak, or a reduction in maximum unsupported excavation span or stand-up time beyond that required for the safe and economic mining of the area of active operations.

Thus, in this review, damage will primarily be concerned with overbreak and potential overbreak, which is controlled by the extent of induced fracturing or cracking. Differences in overbreak, or where there is no overbreak, differences in the degree of blast-induced fracturing, between explosive products or systems will be taken as differences in the damage potential of explosive products or systems.

1.2 IMPACT / COSTS OF DAMAGE

The impact of blast induced rock damage on mining include (Singh, 1992):

(a) dilution (slower "metal" production rates due to increased volumes of waste to handle, lower head grades)

(b) ground control problems (rock falls, increased scaling time)

(c) fragmentation problems (time lost to handling oversize material in draw points)

(d) restricted access to damaged ground for drilling and charging operations

(e) reduction in moduli and strength of rock (pillar failures)

(f) reduction in the maximum unsupported span and stand up time

(g) breakdown of the inherent interlocking of joints

(h) increased cost in the installation and maintenance of extra ground support

One case study by Forsyth & Moss (1990) in a bedded rock with stress induced and blast enhanced damage, by eliminating corner holes (which reduced both damage and stress concentration) and reducing explosive strength along the perimeter (reducing damage), increased weekly advance rates four (4) - fold. The increase in advance was a result of reduced scaling time, reduced mucking time and less time spent on tunnel remediation from the progressive failures.

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2.0 DECOUPLING
2.1 PRELIMINARY

Experience shows that when using regular columnar explosive charges, the best wall control results (with respect to the least amount of blast damage) are obtained when the explosive charge is decoupled from the blasthole wall (Day, 1982).

When a charge is decoupled several effects are occurring.

- there is a reduction in linear density of explosive strength;
- direct transmission of the detonation shock wave to the rock is prevented by a cushion of air (of course assuming that there is no water present in the holes to fill the annulus;
- the borehole wall is pressurised with a lower initial gas pressure as the detonation gases have a volume of air to initially expand into before stressing the borehole walls; and
- there can be a potential change in detonation characteristics / behaviour towards a less ideal state, as it is believed that the decoupled charge will detonate as though it is unconfined. This will give a different shock / gas energy split.

2.2 EFFECTS OF DECOUPLING - EXPERIMENTAL RESULTS

Some very interesting results on the damage potential of various explosives have been reported by SveBeFo (Swedish Rock Engineering Research Foundation). SveBeFo test fired a variety of explosives in development size blastholes, in a surface granite quarry at Vanga in Sweden and then cross-sectioned the granite after removal of the blasted bench as a quarry block. (The granite had strength characteristics of 197 Mpa UCS, 12 Mpa Uts - Olsson & Bergqvist, 1993). After dye-ing the cross-sectioned granite block and examining the damage patterns, the following were found:

(a) the maximum damage crack length decreases as the coupling ratio decreases (i.e. decoupling increases);

(b) fully charged holes, even of extremely low relative explosives energy give greater maximum crack lengths than equivalent energy decoupled explosives;

(c) crack lengths increase with increases in charge size, even for the same decoupling ratios.

(d) The presence of half-barrels is not a guarantee of low damage (in terms of deep fracturing) and therefore can be a misleading measure of damage (this is discussed further in a separate section on Half-Barrels and Damage). The absence of half-barrels can be a reasonable relativemeasure of presence (but not extent) of overbreak, provided sufficient time has elapsed before an evaluation is made (allowing for scaling and stress relaxation);

(e) Explosives with a high detonation velocity gave more cracks close to the hole than low VOD explosives (Olsson, 1996) (this is discussed further in a separate section on High vs. Low VOD Explosives);

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2.3 EFFECTS OF DECOUPLING - FINDINGS

Finding (a), the decrease in damage with decreasing coupling of the explosive in illustrated in Figure 13.

Finding (b), that fully charged holes give greater maximum crack lengths that equivalent energy decoupled explosives is illustrated in Figure 14, where only the 38mm diameter hole results given in Figure 13 are shown, having been rearranged in order of decreasing maximum crack length. The approximate energy density is also shown in the same figure.

From Figure 14. it can be seen that the 22 mm Gurit (VOD - 2,200 m/s) gives a shorter maximum crack length than Emulet 20 (VOD - 1,850 m/s), despite a higher linear energy density in the hole. Similarly, 22mm Kimulux (VOD - 4,800 m/s) gives a shorter maximum crack length than 22 mm Gurit, despite a higher linear energy density in the hole.

Unfortunately Ouchterlony (1995) does not test ANFO or any other dry hole product (it can be assumed that the test quarry, Vanga, in the open-air of Sweden, is wet). Practical experience and observation indicates that the damage potential of ANFO, especially in a weak incompetent and highly structured rock is very high.

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3.0 CRACK LENGTH
3.1 CHARGE SIZE

FIGURE 13. Maximum Crack Length Measured for various explosives and decoupling ratios (for single hole detonations) (data from Ouchterlony 1995)

(NB: Gurit is a NG sensitised emulsion “tube explosive”)
(Kimulux is an AN emulsion “sausage” explosive)
(Emuiet is an emulsion & polystyrene bulk explosive, where)
(Emuiet 20 has 20% REE wrt ANFO)
(Emuiet 50 has 50% REE wrt ANFO)
(Detonex is a detonation cord explosive, where)
(Detonex 40 has 40g PETN / metre)
(Detonex 80 has 80g PETN / metre)

Finding (c), that crack length increase with increases in charge size, even for the same decoupling ratios, was shown when SveBeFo tested 17mm Gurit in 51mm holes and 22 mm Gurit in 64 mm holes. Olsson (1995) gives the crack lengths as listed below:

CHARGE DIAMETER	HOLE DIAMETER	COUPLING RATIO	CHARGE DENSITY	CRACK LENGTHS (CM)
Gurit 17mm	51mm	0.11	0.21kg/m	5cm
Gurit 22mm	64mm	0.12	0.40kg/m	15cm

3.2 ENERGY DENSITY

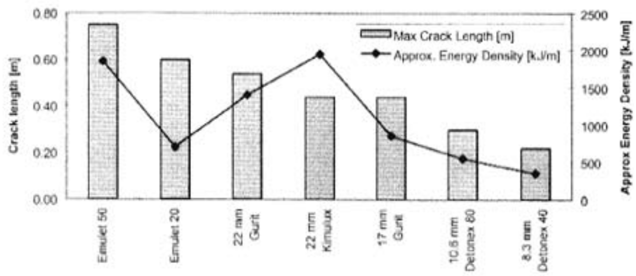

FIGURE 14. Maximum Crack Length measured for various explosives (and decoupling ratios), all in 38mm holes and calculated approximate linear energy densities for the explosives used (crack data from Ouchterlony 1995; and explosive energies taken from Persson , et al 1993).

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3.3 EFFECTS OF DECOUPLING -THEORETICAL ASPECTS

The effect of decoupling on the confined behaviour of packaged explosives can be explained by considering Figure 15. The confinement only influences the VOD if the expanding explosive interacts with the borehole wall before the end of the reaction zone (CJ Zone) which drives the detonation (Du Plessis, Wallace & Tipping, 1987)

4.0 DAMAGE FROM HIGH VS LOWVOD EXPLOSIVES

(Emulsions vs ANFO vs diluted ANFOs)

4.1 GENERAL DISCUSSION

It is often observed in practice that ANFO tends to cause much more overbreak damage than emulsion explosives.

A number of factors are involved in causing the differences in damage, including

- a difference in the energy release rate (a function of the different VODs);
- a difference in borehole pressurisation extent and rate; and
- a difference in the damage modes and extent of energy transmission to the surrounding rock

A key to the differences in the damage caused is the strain rate, i.e. the rock response to the generated borehole pressure of an explosive is some order of magnitudes slower than the rock response to the explosive shock - generated strain wave (Sheahan - file note). This is an effect that is not modelled in the elastic response model in CpeX, implying that CpeX generated explosive ratings cannot be directly related to observed damage.

In the case of an emulsion much of the initial “shock” - strain wave energy and the high detonation gas pressures appear to be expended in very high, severe plastic or crushing deformation localised to the near region around the borehole (Persson, 1990). Additionally the expected effect of the crushed zone on the late-time generated detonation gases would be:

(a) the entry of gases into the cracks would be hindered by the powdery or plastically deformed material within the crushed zone; and

(b) the high specific surface area of the particles within the crushed zone would absorb a significant amount of the heat from the gases, thereby reducing heave energy (Hagan & Gibson, 1988).

An emulsion therefore will have a smaller percentage of gas energy to effect longer range overbreak damage.

In the case of ANFO, the borehole pressure generated I roughly half that of emulsions and is also formed at a slower rate. ANFO therefore causes less intense crushing and is able to produce more long range damage.

The crushing obviously occurs when the expanding strain wave exceeds the dynamic breaking compressive strain of the rock. Where the peak strain at the blasthole wall is sufficient to cause crushing, crack lengths in the inner and outer radial facture zones increase linearly with peak strain (Hagan & Gibson, 1988). As the peak strain increases above dynamic breaking strain, the effect of peak strain increments on the lengths of the radial cracks has not been established (Hagan & Gibson, 1988). Hagan and Gibson (1988) propose that the crushed zone acts as a peak strain “governor” , and increases in the explosion pressure or energy of charges do not necessarily lead to larger fractured zones.

Some of the experimental evidence supporting this theory follows.

4.2 ENERGY LOSS IN CRUSHING

Research by SveBeFo (Olsson, 1995-1996; Ouchterlony, 1995) shows the existence of much greater cracking close to the hole with a higher VOD explosive (Kimulux at 4,800 m/s) compared to a lower VOD explosive (Gurit at 2,200 m/s). Two different crack densities for charges of the same decoupling ratio, but different VOD, are shown in Figures 17(a) and 17(b). Despite the increased crack density closer to the hole, and the higher energy density, the maximum crack length for the Kimulux charge was on average less that of the Gurit (for the 5 holes of each tested), as shown in Figure 14 (in section on decoupling).

Olsson (1996) believes that this more intense crack zone appears to “absorb” some of this extra energy.

Experimental work by Krasavin (1992) led his to also believe that the near zone of an explosion acts as a filter system, letting through one package of wave components and stopping others. He showed that in order to decrease the dissipative losses in the near zone around the borehole and thus redistribute the energy of an explosive to the useful forms of work such as fragmentation and heave, it was desirable to avoid explosives with high detonation characteristics. As the mechanisms of fragmentation are similar to the mechanisms causing damage, it would appear that the obverse, high detonation characteristics, are desirable for lowering damage.

FIGURE 17. Comparison of crack patterns for two explosive charging configurations with similar Decoupling ratios (after Olsson , 1996). (Note different depths of damage; also not necessarily to scale.)
(a) 22 mm diameter Kimulux in a 64 mm diameter hole
(b) 22 mm diameter Gurit in 64 mm diameter hole

Experimental results by Persson, Ladegaard-Pederson & Kihlstrom (1969), shown in Figure 18, show how the breaking effect (in terms of burden able to be removed) of a given fixed energy density charge (0.07 kg/m) increases with increasing hole diameter up to a maximum, when the hole diameter is twice that of the charge, and then decreases (Persson, 1990). As well as possibly indicating the extent of loss of energy in the near hole crush zone for the smaller diameter hole, the result may also be influenced by different detonation characteristics as a result of the different decoupling ratios of the lower two diameter results.

4.3 LOW PULSE DURATION

Low pulse duration explosives (high VOD) gave less time for crack growth and therefore less damage.

Singh (1993a) reports some experiments involving the driving of nine 1.8m long, 2.4m x 2.1m rounds into the bench of a quartzite quarry (UCS - 250 MPA & V 4,800 m/s), using 32mm blastholes. Five different types of explosives were used in the drift round side holes to examine th damager caused by these different explosives. The damage was assessed by overbreak measurement, diamond drill coring and logging the diamond drill holes by borehole camera. Results are show below:

TYPE OF EXPLOSIVE	VOD (M/S)	PEFF (MPA)	MAX THICKNESS OF OVERBREAK (M)	TOTAL DEPTH OF DAMAGE (M)
High Strength Detonating Cord	5,500	766.5	0.11	0.35
Low Strenght Emulsion (sg 1.14)	5,100	4083	0.12	0.525
High Strenght Emulsion 9sg 1.17)	4,600	3409	0.21	0.775
Semi-gelatine dynamite (sg 1.32)	2,800	729.9	0.25	0.80
Diluted ANFO	2500	-	-	1.025
Cord Traced ANFO	-	-	-	1.20

TABLE 1. Observed maximum overbreak and total damage depths for different explosives in competent Rock (Singh, 1993a)

The results of Singh (1993a) show a clear trend with the least depth of damage and the lease overbreak being caused by the highest VOD explosive, with increasing damage and overbreak depth occurring with decreasing VOD.

4.4 CONTROLLING THE RATE OF ENERGY RELEASE

Hagan & Gibson (1988) propose that it is possible to reduce or eliminate crushing and associated energy losses through improved charge designs, based upon the dynamic breaking compressive strain of the rock.

Leiper & Du Plessis (1987) state that control of the ideality of a composition is a mechanism for optimising brisance (the shattering effect) and heave in a blast. It appears from the experimental evidence presented, that long range crack damage is reduced by using an explosive that reacts quickly and as close as possible to ideality, and that near borehole crushing damage is reduced by decreasing the borehole detonation pressure, generally requiring greater new ideality with lower VOD explosives, lower density explosives or decoupling.

5.0 HALF BARRELS & DAMAGE

5.1 DISCUSSION

The visible presence of half-barrels is often considered as evidence of good control over blast induced damage. Being the simplest quantitative measurement available, it is common practice to measure the percentage of perimeter drill hole traces, also know as half-barrels or half-casts (and stated as Percentage Half Barrel Factor, of %HBF) as a measure of blast induced damage, or rather as a measure of lack of damage. The %HBF is sometimes even used as a “quality of work” measure in development contracts (usually only in civil construction contracts).

The presence of half-barrels must however be used with caution - it does not mean an absence of damage! Numerous published experimental results have shown damage behind visibly good rock faces with the presence of half-barrels. The absence of half-barrels can however be a reasonable relative measure of presence (but not extent) of overbreak, provided sufficient time has elapsed before the evaluation is made (allowing for scaling and stress relaxation);

McGroarty (1984) in testing several wall control techniques underground found that the evaluation of pre-split performance using the presence and condition of half-barrels did not agree with rock quality established by diamond drill core fracture density analysis. Similarily, Ouchterlony et al. (1993) found that surface observations were not necessarily representative of the penetration depths of blast induced fractures, although they did find the most of the induced fractures were located around the location of missing contour hole traces of a development round (i.e. no half-barrels).

The most extensive piece of published research into the relationship of damage ot the presence of half-barrels is provided by the research undertaken by SveBeFo in the quarry at Vango. Olsson (1996) found that in some cases the presence of half-barrels and a even a rock surface that appeared in good condition, did not necessarily mean low damage. In certain situations as the hole spacing was increased, despite the presence of half-barrels and good surface condition rock, there existed large bow shaped cracks behind the rock surface.

5.2 SVEBEFO VANGA QUARRY TEST RESULTS

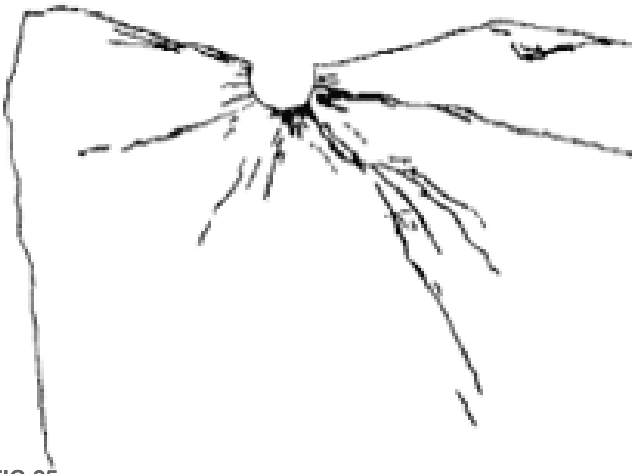

FIG 25

FIG 26

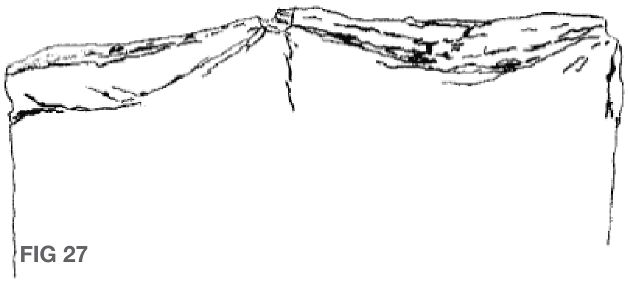

FIG 27

The SveBeFo research reported by Ouchterlony (1995) and Olsson (1995,1996) directly challenges the belief that visible half-barrels traces were found to be no guarantee that the rock behind is undamaged!

The Vanga quarry tests involved the test firing of a variety of explosives in development size blastholes, in a surface granite quarry. The rock around the fired holes was then removed as a quarry block, cross-sectioned, dyed and examined for the damage pattern.

All the holes tested resulted in half-barrels, with the exception of the fully coupled holes, where the hole traces were damaged by the blast. It was found that despite an excellent quality face with half-barrels present, upon cross-sectioning the granite blocks showed severe damage zones (intense cracking).

Two of these damage cross sections are shown in Figures 25 and 26.

It appears that despite a significant amount of strain-wave ("shock") induced cracking behind the blasthole, the lower gas pressures and possibly low gas confinement time have meant that the slower subsequent gas penetration into the cracks was minimal and insufficient to "prise" the cracks open and thereby remove the rock.

An interesting observation noted by Olsson (1996) was that as hole spacing was increased the cracks occasionally formed a bow between the holes as shown in Figure 27. When this happens, both the surface of the rock and the hole traces / half-barrels usually appear to be in good condition. Despite this good appearance of the rock, bow formed cracks could still lead to considerable overbreak in a tunnel.

FIGURE 27. Cracks forming bows between the holes with increased hole spacing (after Olsson, 1996)