Low-density ammonium nitrate fuel oil to improve gold recovery

by K.K. Kabongo*

Synopsis

Blasting in a gold mine has to satisfy the following set of techno-economic conditions: good fragmentation, minimum stope width, minimum number of rock falls, cost effectiveness.

Results of a comparative study of the performance of a Low Density Anfo (LDA) and a conventional Anfo (ANFEX) are discussed. LDA appears to be more cost-effective. The same borehole volume can be charged with material of reduced specific gravity. The velocity of detonation (VOD) is increased in the case of LDA resulting in more breakage as a result of shock energy than from the energy in the gas phase. This leads to less damage to the excavation and more favourable breakage of the excavated rock. As a result the overall economics of the mining operation is improved.

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Introduction

Ammonium Nitrate Fuel Oil, commonly known as ANFO, or ANFEX (a trade name registered by AECI), in mining industry jargon, is an excellent explosive charge for large scale blasting as it combines both performance and low cost. It is used mainly in dry holes, but can be used in wet-holes, provided it is properly packed in special water-proof packages before being inserted into the blast holes.

ANFO performs well in large diameter holes in both hard and soft rock provided that it is well charged and properly confined. The density ρ of ammonium nitrate is a very important parameter as it greatly influences the effectiveness and the overall performance characteristics of the mixture. It is considered to be the technical parameter to be controlled by the manufacturer so as to obtain the optimum efficiency of the product.

The conventional density of ANFEX produced by AECI is 0,76 g/cc. The need to develop a lower energy explosive for stoping has prompted the production of the low density ANFEX (LDA) at a density of 0,67 g/cc. In France, the Grande Paroisse Company has succeeded in lowering the density to 0,64 g/cc.

Experimental work done by Vuillaume[1], corroborated by the results obtained in South African gold mines, confirms that the LDA in small diameter holes yields a higher in-hole VOD than the conventional ANFEX. The trend has been observed both in a blasting range where the products were detonated both in small and large diameter steel pipes as well as in boreholes drilled in rock *in situ*.

The shock pressure and consequently the shock energy increase as the density of ANFEX decreases. The highlight of this understanding of recent years illustrates the importance of a careful approach to blast design and represents a change in the previous concept which was based on the work of Johansson and Persson[2] in 1970, which claims that the higher the density of the explosive, the higher the VOD.

It is the intention of this paper to report on field observations made in four South African gold mines where LDA and conventional ANFEX have been used in an attempt to compare their performances. The observed trend in narrow stopes employed in gold mining is toward a decrease in the blast violence (damage to the rock) by using a lower density ANFEX, thus achieving an improved stope width underground.

Improvement in the recovery of gold

Despite the strength of gold-bearing rock, too much energy in blasting results in over fragmentation and losses of gold in the fine fractions produced. This tends to be detrimental to the economics of the overall mining operation.

A high shock energy component in a blast implies the use of explosives with a high VOD. This ensures creating an important network of cracks in the rock, hence more breakage (fragmentation) leading to a greater degree of liberation of gold particles.

Excessively fine particles are normally not desirable in gold mine blasting practice. The fine material is not easy to collect in subsequent loading and handling operations and losses of gold can result.

The customary way of reducing gold losses is the use of less violent explosives involving a greater heaving effect than shock effects. The use of watergel, rather than emulsion type explosives, would be advisable. The use of decoupled nitroglycerine based explosives is also a good option. However, these products are less user-friendly and more costly than ANFEX, and LDA appears to be the best choice to achieve optimum results.

Tests of low density ANFEX versus conventional ANFEX

Conventional ANFEX and Low Density ANFEX were tested in stopes of a highly carbonaceous reef in South African gold mines. The tests were conducted in a stope at approximately 2550 m below the surface. The breast mining method was used, with the stope divided into three 30 m long panels. The average thickness of the reef mined was approximately 300 mm. The potential stope width (mining width) was 950 mm. The reef dip was approximately 22 degrees. The hangingwall rock was a glassy quartzite having a uniaxial compressive strength of 276 MPa. The footwall quartzites were sub-glassy to slightly argillaceous, with a compressive strength of 123 MPa. Numerous bedding planes were visible. The interbedding material was a shale filling of variable thickness.

A typical fracture pattern found in deep level gold mines as a result of mining-induced stress concentrations is shown in Figure 1.

Box-cut drilling

Gold mining methods differ from other mining methods in that, in gold mining, relatively small volumes of rock are fractured in one blast in order to maximize profit. In gold mines the direction of mining follows the reef direction. A compromise has to be found between minimum possible waste rock produced by the blast and the maximum possible recovery of gold from the reef. Such a working constraint dictates a selective mining approach in which blasting is conducted just above and below the reef and is directed towards the highest possible gold extraction (Figure 2). Blast holes are drilled by hand-guided rock-drills supported by thrust legs. Drill stems of 0,9 m effective length of 42 mm diameter are used.

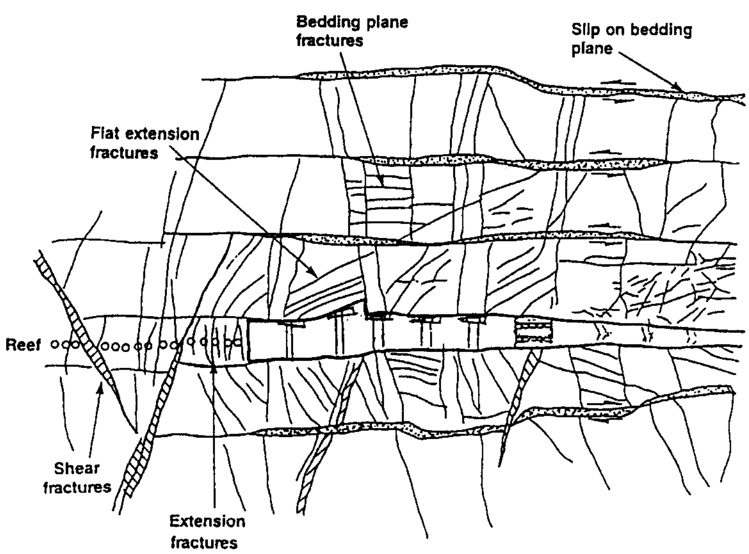

Figure 1—Typical fracture pattern in deep-level gold mine stopes (COMRO, 1988)

The drilling pattern in reef blasting in South Africa, consists of two rows of drill holes with a variable burden-to-spacing ratio depending on local conditions. Horizontal hole angles are normally less than 90 degrees to the advancing stope faces in order to provide favourable breaking at the toe, and to promote maximum face advance. The vertical holes are drilled as flat as possible.

The initiation line consists of 1,2 m long fuse at the end of which a cap sensitive 6-D detonator is crimped. The other end is connected to a length of ignitor cord used to ignite the blast. A 22 x 100 mm gelignite primer pushed at the bottom of the hole serves to boost the detonation from the 6-D detonator.

Explosives characteristics

The mixtures of ANFEX used in the blasting tests described are detailed in Table I.

Geometry of the blast

In narrow stopes of gold mines, the effective charge is sized to suit the burden. Brinkman[3] worked out the following equations, which are used in most gold mines of South Africa:

$$\text{Burden}(B) = [(Ee)^{0,5}\ (\sin\theta/2)^{1,5}]/[(1{,}06\ KC)]. \quad [1]$$

and

$$Ee = [(1{,}06\ KCB)^2]/[(\sin\theta/2)^3]. \quad [2]$$

where B is the burden distance at the hole bottom, m
θ is the breakage angle
K is the explosive factor, 1,0 for ANFEX
C is the rockmass strength
SW is the stoping width (m)
HS is the hole spacing (m)
D is the increase in burden at the hole bottom due to inaccurate drilling (m); hence ($B = HS + D$).
C = 1,4 for hard unfractured rock without bedding planes.
C = 1,2 for a rock with a high-energy release rate(>30 MJ/m^2).
C = 1,0 where the breakage is directed towards the bedding planes in the hangingwall and footwall.

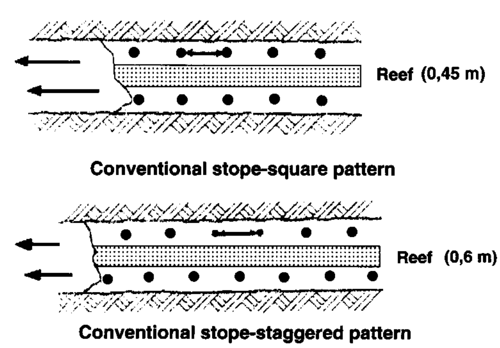

Figure 2—Drilling and blasting patterns in narrow gold reefs

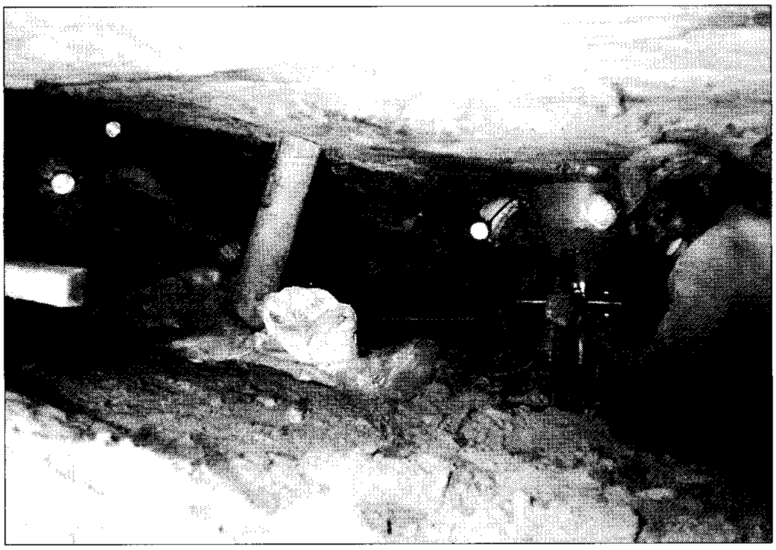

Figure 3—Pressure/venturi type of ANFEX loader

Table I

Explosive characteristics

Parameter	ANFEX*	LDA
Density, g/cc 0,79	0,70	
Bulk density loaded, g/cc	0,8 – 1,05	0,7 – 0,95
Bulk strength (ASV), MJ/kg	2,6	1,9 – 2,5
Relative weight strength	100	100
Relative bulk strength	100	88,6
Velocity of detonation, m/s	3500–4500	3000
Effective energy, MJ/m	1,969	1,667
Specific energy, MJ/m^3	7,436	6,292

* ANFEX was pneumatically loaded into blast holes by means of a Lategan pressure/venturi loader (Figure 3). Although AECI has the technology to produce LDA at 0,63 g/cc, the actual material supply used in the test had a density of 0,7 g/cc.

$$\theta = \arctan\,[2\,SW/(HS + D)] \quad [3]$$

for a staggered hole pattern

$$\theta = \arctan\,[SW/(HS + D)] \quad [4]$$

for a square hole pattern.

For the first hole to fire of a vertical pair, and $\theta = 90$ degrees for the second hole to fire.

where *SW* is the stoping width, m
HS is the hole spacing, m
D is the increase in burden at the hole bottom due to inaccurate drilling, m; hence $(B = HS + D)$.

The values of these parameters are given in Table II.

Table II

Blast geometry parameters

Burden (staggered), m	0,44
Burden (square), m	0,31
Breakage angle (staggered), °	70
Breakage angle (square), °	54
Powder factor, kg/m	2,86

Control of the stope width

It is imperative in gold mining to maintain the stope width constant or possibly to reduce it, in order to ensure minimal contamination from waste material and better selectivity underground. This is achieved by the use of a low energy input to fracture the rock. Thus, less damage to the remaining stope rock, as well as to supports and blasting barricades can be achieved. Greater stability and hence safety in the stope is ensured. Strict supervision was maintained over the drilling crew so as to ensure accurate drilling. The charging pressure was closely controlled at a constant value to ensure that it would not be a variable factor influencing the performance of the various explosive mixtures and the resulting stope width.

A summary of the test results show that a reduced stope width with better control of the hangingwall was achieved by using the Low Density ANFEX (Table IV).

It was even possible to further reduce the stope width, from 1,0 m to 0,6 m as shown in Figure 4. Unfortunately, such a stope width could not be implemented in practice as the human effort to work in it became too demanding so that it was ultimately decided to increase the stope width. A 17 per cent reduction in stope width was achieved in practice. This brought about a considerable decrease in costs, due to less tonnage handled, less contamination of the gold, and reduced support and transportation costs.

Fragmentation

In narrow gold-mine stopes, the average fragmentation size, D_{50}, can be predicted from the following equation[3], which is recommended by the South African Chamber of Mines:

$$D_{50} = P[1 - [(0,8)(ERR)/100](SE)^{-1,5} \quad [5]$$

where D_{50} is the average fragmentation size in mm
P is the explosive factor,
ERR is the energy release rate, MJ/m^2
SE is the specific energy in MJ explosive energy per m^3 of *in situ* rock.

$P = 566$ for ANFEX. *SE* can also be computed from the powder factor (*PF*) and the absolute strength value (ASV) of the explosive using the relationship:

$$SE = PF \times ASV. \quad [6]$$

Table III compares the fragmentation obtained, using conventional ANFEX and LDA.

Table III

Observed fragmentation

Size range, mm	ANFEX	LDA
0 – 25	21 %	24 %
25 – 50	16 %	19 %
50 – 100	24 %	24 %
100 – 200	24 %	22 %
+ 200	15 %	11 %
D_{50}	62,6 mm	74,0 mm

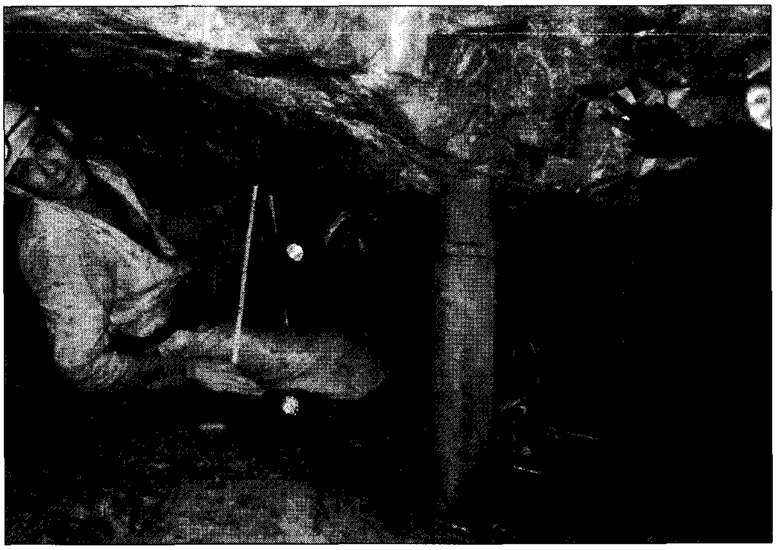

Figure 4—Reduced stope width (0,6 m) achieved when LDA was used

Table IV

Performance results obtained using conventional ANFEX

Month	Broken m^2	Width (cm)			Cost R		
		Face	Stope	Δ (%)		kg/m^2	kg/m^3
January	4727	108,6	112,4	3,5	17 731	3,059	2,721
February	4857	108,8	110,3	1,4	20 239	3,398	2,080
March	5146	115,4	120,6	4,5	–	–	–
April	6137	116,8	124,1	6,3	22 564	2,998	2,415
May	6243	113,8	119,5	5,0	20 359	2,659	2,225
June	6248	109,3	114,0	4,3	23 048	3,007	2,637
July	6562	113,3	119,0	5,0	21 205	2,634	2,286
Average	5703	112,3	117,1	4,3	20 858	2,959	2,394

Table V

Performance obtained with LDA

Month	Broken m^2	Width (cm)			Cost R		
		Face	Stope	Δ (%)		kg/m^2	kg/m^3
August	6433	106,8	107,9	1,0	19 332	2,205	2,043
September	6391	102,4	113,3	10,6*	18 456	2,119	1,870
October	6120	98,8	110,6	11,9*	16 946	2,032	1,837
November	6016	99,6	104,4	4,8	15 405	1,879	1,799
December	6227	100,0	105,8	5,8	18 426	2,413	2,280
January	5549	101,4	106,1	4,6	13 494	1,784	1,681
February	6066	103,1	106,1	2,9	23 614	2,856	2,681
March	6140	103,1	103,1	0,0	20 873	2,495	2,419
April	6246	86,7	92,5	6,7	16 645	1,955	2,113
May	5015	94,5	94,5	0,0	18 411	2,694	2,866
Average	6020	99,6	104,4	3,2	18 160	2,243	2,159

Δ Excess stope width

* Discarded as very isolated values

Face advance

Optimum stoping aims to achieve the maximum face advance by minimizing the length of the sockets resulting from the blasts.

The hole depth is always dependent on the desired stoping width, the stope support limitations, and the drilling accuracy.

Successful blasting requires that the breaking energy of the explosive charge (effective charge) be matched to the burden geometry and the rock conditions (geology). A charge which is effectively too large for the burden increases the violence of the blast unnecessarily. An undersized charge produces a long socket and a greater proportion of large rocks that will inhibit face cleaning operations.

An average reduction in socket length of 5 cm was observed with the use of Low Density ANFO which corresponded to an improvement of almost 5,5 per cent in advance. This was attributed to the low susceptibility of LDA to sympathetic detonation, which implies lower degree of desensitization of the explosive in the blasthole.

Cost savings

Major cost savings have been achieved from the improved explosive efficiency realised using Low Density ANFEX. The explosive consumption per unit of stope face area was observed to drop from 3,0 kg/m^2 to 2,2 kg/m^2, corresponding to a 27 per cent saving in explosive usage, valued at R2698 per month (Tables IV and V). Ten per cent gain in powder factor has been achieved.

Another series of investigations on the use of LDA was conducted at a second South African gold mine. The LDA was manufactured by AECI at a density of 0,64 g/cc and relative energy of 90 per cent. A study was conducted to evaluate the relative performance of this LDA as compared to the conventional ANFEX. A total of 42 blasts at stope faces were conducted using LDA against 27 using the normal conventional ANFEX. The blasting conditions were kept the same so as to ensure a fair comparison. The blast results were assessed by photography.

From the results of these investigations no conclusion could be drawn as to whether the use of LDA leads to a significant improvement of the stope width. The mine has never experienced major problems in hangingwall control. This is mainly ascribed to the smooth parting at the top reef contact. However, underground observations showed that there was a distinct difference in concussion experienced by the rock. The hangingwall in the stopes where blasting was conducted using LDA showed minor signs of violent damage as compared to that in stopes blasted with the normal ANFEX charge.

Judging from the visual examinations of the blasted faces, supported by careful observations of the photographs, it appeared that fragmentation was improved in the blasts using LDA. Far more larger than 100 mm sized rocks and less fine fractions could be identified than in the case of a normal ANFEX blasts. However, curiously, the supports in the panels after LDA blasts sustained more damage (timber props and barricades). This has been attributed to the increased mass of broken rock involved, some of which could have resulted in loose hanging blocks in the hangingwall if the normal ANFEX was used. The relatively poor heave pressure resulting from the increase of the speed of combustion in the LDA appeared to have had the effect of increasing the kinetic energy of the rocks. Thus, a considerable impact force could have been generated.

A third mine surveyed in the South African mining industry where ANFEX and LDA have been used, experienced a reduction of the monthly average tonnage of 40 per cent (from 72 677 t in July 1992 to 42 957 t in May 1993) by using LDA in place of ANFEX.

The tonnage decrease was believed to result from smaller face areas mined, as well as a decrease in the overall stope width. Obviously, other mining parameters such as the depth of the holes (shorter drill steel), the variability of the channel width and the training of personnel have a share in such excellent results. Nevertheless, the role played by the explosive charge (LDA) towards the recorded results was clearly indicated.

Summary

In summary, LDA has been used in four mines monitored for the purpose of comparing its performance with the conventional ANFEX. The following observations were made:

1. The first mine:
   - One shaft achieved an average stope width reduction of 16,2 cm in a three-month period.
   - A second shaft achieved a 10 cm reduction over 40 000 centares in one month.
2. The second mine:
   - A sensible reduction in overbreak implying:
     - fewer falls of ground and less working time losses underground
     - considerable savings realized in re-establishing faces and pillar cutting.
3. The third mine:
   - The fragmentation improved, (an increase in material larger than the 100 mm fraction and a decrease in material smaller than the 1 mm fraction).
   - A 20 per cent decrease in falls of rock (from 4,5 to 3,6).
4. The fourth mine:
   - A stope width reduction of 34,9 cm in four months
   - A gold recovery increase of 0,55 g/t
   - A fragmentation improvement in the processing plant feed, and
   - Support costs were reduced.

Discussion

LDA appears to be more cost-effective than the normal ANFEX. Larger volumes can be charged with lower specific gravity under controlled charging conditions. This is made possible because LDA prills are less denser than the normal ANFEX ones. Thus, the same volume of hole is filled up with a smaller mass of LDA at the same price per unit mass. The basic ingredients used to manufacture both products are the same the only difference that the high technology process used in the LDA cooling tour provides it with more micro-pores.

For the same prill size, LDA has more internal void space than ANFEX. (The French company of Grande Paroisse claims to be able to produce as much as 11 per cent void space in LDA prills.)

The void spaces in the prill improve the absorption of fuel oil for LDA which in turn improves the stoichiometry of the explosive mixture (5,7 per cent fuel oil for 94,3 per cent of AN). In addition, the additional void space is used to generate heat centres in the detonation (hot spots). The greater the number of hot spots in detonation, the higher the velocity of propagation of the shock front and the higher the VOD. Consequently, since the ingredients in both materials is almost the same, LDA is the more cost effective explosive charge per unit weight.

With regard to the performance, it is indicated that use of LDA results in significantly less violent detonations, which helps to minimize fines and overbreak. This establishes LDA as the most suitable explosive for use in gold mining blasting.

It has been argued that, at the operational loading pressure underground of 3 to 4 bars in the Lategan charging device, LDA prills are compressed in the shot hole. The void spaces are suppressed, and theoretically its detonation behaviour should not be different from the one of ANFEX.

Experience in the field has shown that, even under undesirably severe loading conditions, the LDA blast gives comparatively better results. This can be ascribed to the residual void spaces remaining despite compression and the high degree of inter-particle fuel absorption claimed for the LDA mixture. The information to hand indicates however that LDA densities, even after pneumatic loading, are less than those of normal ANFEX. Cunningham can be quoted as saying:

'At this point in time, AECI can only say it works in the field'.

Suitable blasting technology in gold mining is expected to yield good fragmentation for a maximum stope advance while maintaining quality control of both the excavation and the excavated rock. Johansson and Persson[2] assert that the lower the density, the lower the velocity of detonation and the less the shock energy generated during the explosive reaction. This assertion has given rise to the common rule-of-thumb which states that, the denser the explosive, the higher the VOD, and the more suited it is to blast hard rock. However, it is now realized that fragmentation is a result of a series of complex mechanisms which are very difficult to define the boundaries. The combination of shock and heave energy released by a particular detonating explosive charge has to be related to the geology of the rockmass and the dynamic properties of the strata to determine the nature of the response of the rock in terms of fragmentation.

At the current stage of experience with LDA in South Africa, it appears that no statistically valid conclusion regarding the fragmentation performance can be drawn. The observed fragmentation results (Table III) do not show any significant differences between the two formulations. The proportion of minus 25 mm size fractions appear to favour ANFEX. The plus 200 mm size proportion is however increased by 35 per cent. The percentage of the mid-size (good fragmentation) seems to be slightly in favour of LDA.

Modern commercial explosives are manufactured with voids (bubbles, micro-balloons, etc.) to improve the detonation behaviour. Upon initiation, the voids develop into centres of heat concentration (hot spots), which enhance the reaction. This implies an increased VOD. Vuillaume[1] observed a trend of increasing VOD for LDA in both small-scale tests (36 mm steel pipes) and under field mining conditions. Thus, he concluded that the performance of LDA is favoured by the enhancement of the shock effect. Despite the fact that the potential chemical energy in the mixture does not change, the magnitude of the shock to heave ratio does vary. The result is that more energy is imparted to the rock in the shock effect and the contribution of heave effect diminishes. The effective strength of the explosive, which is related to the rock breaking results does increase with LDA, whereas the predominance of the gas phase in ANFEX gives rise to a decrease.

ANFEX is a low VOD explosive charge. In large diameter holes, the in-hole VOD averages 3600 m/sec. In the small holes of 42 mm, generally used in gold mines, the in-hole VOD does not exceed 2000 m/sec. Rock breaking in the stopes in such a case, is the result of a poor crack network created by a low dynamic shock effect followed by a longer quasi-static heave effect. The few radial cracks inherent in the rock are extensively extended, and most likely more damage to the hangingwall occurs. From the point of view of dynamic fracture mechanics, it has been observed that the stress field associated with efficient crack growth is generated instantly with a high amplitude. It induces an acceleration, i.e. a high crack growth velocity characterized by an important bifurcation phenomenon favouring fracture around the borehole. Then, after a short phase of deceleration, the radial shock cracks initiated are invaded by increasing gas stresses, which enlarge and extend them further. In the final analysis, the extension of the radial cracks responsible for the stope damage (stope width increase and back break effects) depends on the importance of this gas effect. In the light of the field investigations, very limited cracks are observed in the hangingwall of the stopes blasted with LDA, corroborating the idea of an increased shock effect in the LDA detonation.

Conclusion

The final density of the product, whether it is ANFO or LDA depends on the charging pressure in the borehole. It is a very difficult parameter to assess accurately as it depends on the human factor, the abilities of the charging crew. Unfortunately, it controls the overall energy repartition in the blast, and it can even lead to a complete desensitization if too high. Nevertheless, the fuel-oil absorption is improved in the LDA mixture due to micro-pores. The shock energy is increased. More primary cracks in the rock are set. The gas effect is reduced, therefore, less damage to the excavation is ensured.

Furthermore, the pressure/venturi charging machine operates on a volumetric principle. A fixed volume of the charge is pumped out, making it easy to achieve reduced weight charge in a borehole when a low density formulation is used. ◆

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