

Article

The Performance Analysis of Pumpable Emulsion Explosives in Narrow-Reef Gold Mines

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Abstract: The use of pumpable emulsion explosives in the stopes of narrow-reef gold mines is an emerging practice. This is due to recent developments in the delivery and placement mechanisms of emulsion and gassing agents through portable charging units into small-diameter blastholes. With these developments, this paper outlines the performance of pumpable emulsion explosives in a non-trial basis at two underground gold mines in South Africa, where a combined 33 underground drilling and blasting outcomes were observed in two shafts, where three key performance indicators—namely face advance, powder factor, and fragmentation size distribution—were evaluated. The results indicated that the use of emulsion explosives can enhance the probability of achieving the target face advance, whereas the results of the powder factor are mixed. In one shaft, the actual powder factor of the observed blasts mostly exceeded the planned powder factor, whereas in the other shaft, the latter was largely achieved. Lastly, the results of the fragmentation size distribution analyses are inconclusive; that is, it cannot be conclusively pointed out whether the use of pumpable emulsion explosives can achieve a mean particle fragmentation range of 11.5 cm to 13.5 cm at Shafts A and B.

Keywords: pumpable emulsion explosives; face advance; powder factor; fragmentation; narrow-reef stopes



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1. Introduction

Blasting is a crucial mining activity that offers the most cost-effective and adaptable means of extracting ore from hard rock mines [1]. The use of explosives has a direct impact on both the production and safety of the operation, which can either have a positive or negative effect on the mine's finances [2]. Blasting is also a strategic activity that influences downstream activities such as the cleaning rate and rock handling (transportation), efficiency factors such as the mine call factor (e.g., loss of gold fines underground), and profitability [3].

This paper focuses specifically on the blast efficiency of pumpable emulsion explosives in the narrow-reef stopes of gold mines located in the Witwatersrand basin. The blasting efficiency is a measure of the quality of a blast, which can be evaluated through several key performance indicators (KPIs), but the focus in this paper is on the face advance, powder factor, and fragmentation size distribution per blast, specifically the mean fragmentation size.

These KPIs are affected by controllable factors such as the blast geometry, marking and drilling accuracies, the choice of explosives, charging practices, initiating systems, and the timing of the round, as well as uncontrollable factors such as the geology and

rock mass characteristics. According to [3], successful blasting requires a blast design that ensures optimal interaction between explosives and controllable and uncontrollable factors to achieve the desired blast outcomes, such as the target advance per blast.

2. Emulsion Explosives Use in Narrow-Reef Mines

The shafts where observations were made use...the narrow-reef stoping mining method typically used to mine the tabular platinum-group metals and gold orebodies in South Africa [4]. The thickness of an orebody varies from a few centimetres to about 200 cm or 2 m, but the majority is typically less than a meter. Figure 1 shows a typical narrow-reef stoping mining method layout used in South African gold mines with a standard five-hole burn cut in the advanced strike gully (ASG).

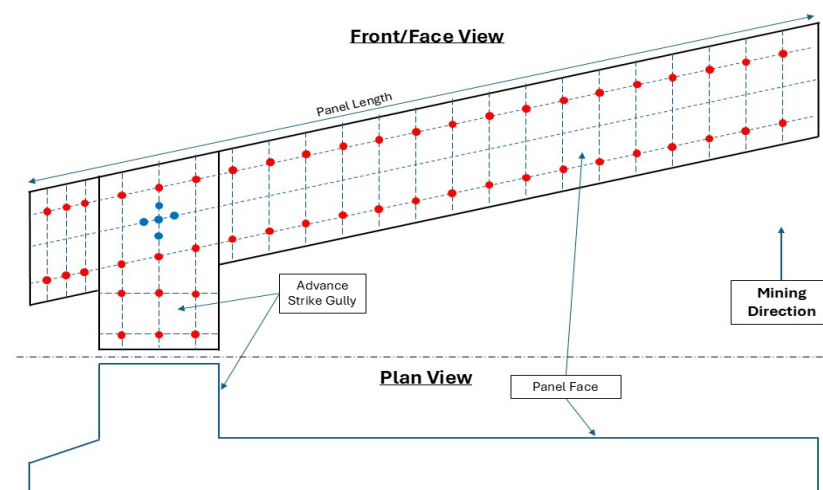


Figure 1. An example of the drill design used at Shafts A and B with a 5-hole burn cut in the ASG. Red dots are blast holes and blue dots are a 5-hole burn cut.

Table 25 m and 30 m. The burden along the face of a panel in a stope typically varies between 60 cm and 80 cm, while spacing varies from 40 cm to 50 cm depending on the stoping height. To avoid drilling into the hanging wall, the first row of blastholes is offset 25 cm from the hanging wall, while blastholes on the bottom row are offset 35 cm from the footwall. Thus, for a 100 cm stoping height, two rows of blastholes are drilled with a spacing of 40 cm. When the stoping height is greater than 150 cm, it is recommended to drill three rows of blastholes. This ensures that the spacing is maintained at around 40 cm for an even distribution of explosives across the panel. The variation in the stope height affects the number of rows drilled and, thus, may affect spacing, but the burden remains unchanged.

Ammonium Nitrate Fuel Oil (ANFO) and cartridge explosives are the most commonly used explosives in South Africa's underground narrow-reef mines. In gold mining, ANFO is typically favoured for dry blastholes in development ends, whereas water-resistant cartridge explosives are preferred for wet blastholes in panels due to the use of water for drill bit cooling and dust suppression during drilling. The use of emulsion explosives in these mines is recent. Emulsion explosives are water-in-oil emulsions containing minimal ANFO, water, oils, and an emulsifier [5,6]. Classified as a 5.1 oxidising agent under the UN3375 code, their reduced harmful product content, enhanced safety features during transport and delivery [6,7], and charging efficiency led to their adoption in South African narrow-reef mines. Historically, pumpable emulsion explosives were formulated with a high explosive density, and due to the inability to modify them given the available pumping technology for underground mines at the turn of the century, their introduction

in underground mines was abandoned [7,8]. Their introduction in narrow-reef stopes came in later, when portable charging units (PCUs) were introduced for use in stopes [7].

Cartridge explosives, particularly in panels, remain a time-intensive option due to the manual process of placing and tamping cartridges into blastholes. The introduction of emulsion explosives in underground narrow-reef stopes offers a more streamlined alternative, effectively rendering the use of cartridges unnecessary in many scenarios. The widespread use of pumpable emulsion explosives in narrow-reef mines was generally hampered by logistical complexities, the unavailability of appropriate charging equipment, and limited research and data on their application in blastholes with a diameter equal to or less than 36 mm typically used in narrow-reef stopes [7].

Pumpable emulsion explosives were introduced in underground narrow-reef stopes as a result of improvements in delivery technology, with a view to improving safety, reliability, and blast performance. Therefore, it has become imperative to evaluate the pumpable emulsion explosives' performance in key areas such as the blast efficiency, post-blast conditions, and explosives' cost.

Mining operations can suffer from a loss of revenue due to a poor advance per blast. The poor advance per blast can be remedied, in most cases, through training, supervision, the choice of explosives, and the control of marking, drilling, and charging practices, as they have an adverse influence on the blast outcomes. A change in any of these parameters influences the effective charge, which is defined as the product of the energy concentration and coupling ratio for specific blast outcomes [9].

The presence of sockets on the face is one of the signs of a poor face advance. Any blasthole longer than 5 cm post-blasting is regarded as a socket [4]. The prevalence of sockets can be used as an indicator of blast efficiency, which can be determined using Equation (1).

$$\text{Panel Socket Prevalence} = \frac{\sum \text{Socket lengths in panel}}{\sum \text{Blasthole lengths in panel}} \times 100 \quad (1)$$

Similarly, the powder factor is important in achieving an efficient blast. The powder factor is the ratio between the mass of the explosives used and the volume of rock broken during a blast. It is also defined as the average amount of explosives used to blast a tonne or cubic metre of rock [10,11] and can be calculated using Equation (2):

$$K = \frac{M_t}{L \times A \times W} \quad (2)$$

where K is the powder factor (kg/m^3), M_t is the total mass of the explosive (kg), L is the panel length (m), A is the advance per blast (m), and W is the stoping width (m).

Generally, in practice, the powder factor is determined through experience, rules of thumb, or blasting indices. These methods rely on the post-blast analyses and adjusting the inputs for the next blast to achieve the desired results. Even where planning and predictive models are used, post-blast analysis is still important [12]. The determination of fragmentation size distribution post-blast is an indication of the adequacy of the powder factor.

It is important to note that the primary objective of rock breaking is to achieve fragmentation within a specific size distribution envelope for the optimal performance of the downstream processes such as loading, transportation, crushing, and milling [11]. Large rock fragments can cause damage to the stope support and barricades and increase the likelihood of secondary blasting, blocked ore passes, and high crusher energy costs, whereas fine fragments can result in gold losses, the risk of mud rushes from ore passes, and more fines than planned being reporting to the milling circuit.

To ensure that the designed blast parameters result in the desired fragmentation size distribution, the Kuznetsov equation is used to estimate the mean fragment size (X_{50}) passing through a screen of a specified size. The expected mean fragment size can be calculated using Equation (3),

$$X_{50} = A \cdot K^{-0.8} Q^{\frac{1}{6}} \cdot \left(\frac{115}{RWS} \right)^{\frac{19}{30}} \quad (3)$$

where X_{50} is the average particle size (cm), A is the rock factor, K is the powder factor (kg/m^3), Q is the mass of the explosive used (kg), and RWS is the relative weight strength.

To assess the accuracy of the Kuznetsov equation prediction of the designed blast and for continuous improvement, the resulting muck pile is subjected to photogrammetric analysis.

3. Methods

The objective of the research was to determine the performance of pumpable emulsion explosives in narrow-reef gold mine stopes, which is constrained, among others, by the parameters in Table 1. The emulsion explosive used was the AEL UG100 series, and the underground data were collected by the first author.

Table 1. Blasting parameters for pumpable emulsion explosives at Shafts A and B.

Parameter	Emulsion and Sensitiser
Drill steel length	120 cm
Effective blasthole length	90 cm
Blasthole diameter	3.2 cm
Planned stemming length	32 cm
Planned burden	60 cm
Expected blast advance (90% of effective blasthole and above)	80–90 cm
Explosives density	1–1.18 g/cc
Initiating system	Shock tube 200/4000 ms
Relative weight strength (RWS @100 MPa)	89 MPa
Relative bulk strength (RBS @ 100 MPa)	127 MPa
Velocity of detonation	4000–5000 m/s
Rock factor (conglomerate/quartzite)	10

To achieve this objective, data were collected from two gold mine shafts in the Witwatersrand basin, with Shaft A mining the Ventersdorp Contact Reef and Shaft B mining the Carbon Leader Reef. The two shafts can be described as conventional mines using hand-held drill machines and the scraper winch systems in the stopes for drilling and cleaning purposes. The conventional mining method is the most preferred in narrow-reef mines because it can navigate complex geological structures, can be applied in smaller stopping heights, which helps reduce dilution, and is relatively cheaper to implement [13].

The blasting data were collected over five months on a non-trial basis from seven panels, labelled Panel 1 to 7, across both shafts, with a total of 33 drilling and blasting observations, as outlined in Table 2. Four panels were observed at Shaft A, with a total of 20 observations, and three panels were observed at Shaft B, with a total of 13 observations. It should be noted that the numbering of blasts does not necessarily mean consecutive blasts but rather the number of blasts observed per panel over a period of time.

Table 2. Summary of blast observations conducted at Shafts A and B.

Shafts	Panel	Total Number of Blast Observations	Blast No.
A	1	5	1 to 5
	2	5	6 to 10
	3	5	11 to 15
	4	5	16 to 20
B	5	5	1 to 5
	6	4	6 to 9
	7	4	10 to 13

Several images of the muck pile profiles of select blasts per panel were taken before cleaning could commence to determine the mean fragmentation size using Split-Desktop (4.4.0.22) and WipFrag Image Analysis Software (2.7.27). The images were captured using a RICOH WG-60 camera. The number of images required to calculate the size distribution of a given sample of material was not fixed, as the selection depended on the quality of the pictures in terms of the visibility and lack of shadows. Figure 2 shows an example of a muck pile image taken underground.

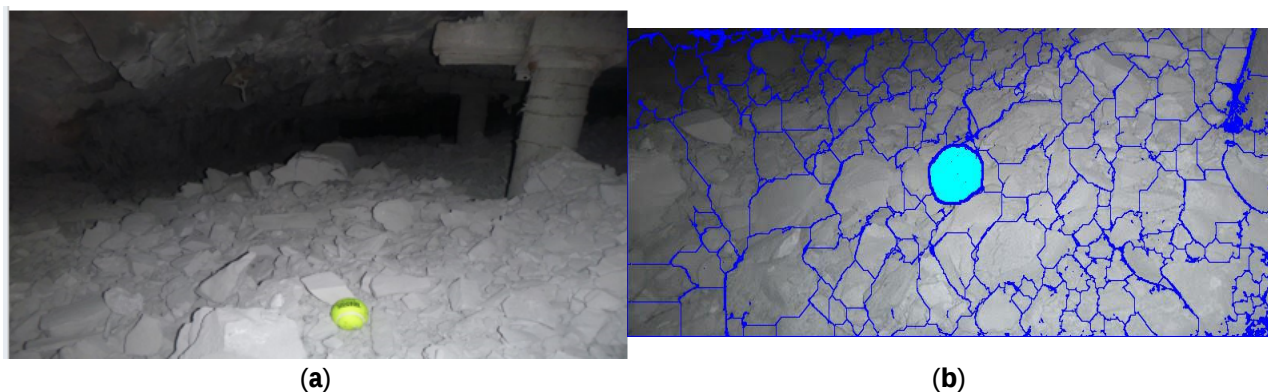


Figure 2. (a) A photo of a muck pile taken underground at Shaft A. (b) A WipFrag analysis of a muck pile photo taken underground [14].

Split-Desktop and Wipfrag Image Analysis software were used to analyse the images. The lighting underground was primarily from the camera, and the cap lamp was used as an additional source of light, while a tennis ball was used as a scaling object. The images were first analysed using Wipfrag (2.7.27) and validated using Split-Desktop software (4.4.0.22). The captured images were uploaded onto each system for analysis in accordance with each system's manual guidance. The system automatically identified the limits of the rock particles and delineated them accordingly, and further manual editing was conducted to enhance the delineation by removing false edges and polylines and to draw missing edges. The size distribution of each muck pile was obtained from a combination of multiple images that were analysed.

With respect to the measurements underground, a measuring tape was used to measure the panel length, width, burden, and spacing, while a 1 m clinometer ruler was used to measure the blasthole angles. Furthermore, the following general observations were made:

- The general reef dip was between 21° and 25° in both shafts.
- In Panel 1, the geological conditions were favourable and the horizontal drilling direction was between 70° and 90°, with an average of 10 cm of underbreak.

- In Panel 2, the geological conditions were favourable, and the horizontal drilling direction was between 80° and 90°, with an average of 0 cm of overbreak.
- In Panel 3, the geological conditions were favourable, and the horizontal drilling direction was between 80° and 90°, with an average underbreak of 5 cm.
- In Panel 4, two faults were intersected, and the horizontal drilling direction was between 80° and 90°, with an average overbreak of 12 cm.
- In Panel 5, the hanging wall had partings, and the horizontal drilling direction was between 88° and 90°, with an average overbreak of 21 cm.
- In Panel 6, the hanging wall had partings, and the horizontal drilling direction was close to 90°, with an average overbreak of 33 cm.
- In Panel 6, the hanging wall had partings, and the face had multiple bands of reefs. The horizontal drilling direction was between 86° and 90°, with an average overbreak of 13 cm.

4. Results

4.1. Face Advance

Table 3 summarises the stoping parameters in Shafts A and B. In Table 3, it can be noticed that in general, the actual stope or panel width at Shaft A is less than planned, while the reverse is true for Shaft B. The drill and blast guideline at both shafts is that for any panel width greater than 150 cm, three rows of blastholes must be drilled and blasted, and two rows are required for panel widths less than 150 cm. With this guideline, it would be expected that the average number of actual blastholes drilled in Shaft B (except for Panel 7) would be higher than the plan, but this was not the case.

Table 3. Summary of the actual panel width and the number of blastholes drilled per blast at Shafts A and B.

Shafts	Panel	Average Planned Panel Width (cm)	Average Actual Panel Width (cm)	Average Planned no. of Blastholes Drilled	Average Actual no. of Blastholes Drilled
A	1	220	207	68	74
	2	180	179	86	85
	3	180	175	82	70
	4	180	192	121	135
B	5	135	156	103	86
	6	142	175	176	148
	7	214	227	122	142

Figure 3 illustrates the measured face advance per blast compared to the target at Shaft A, and Figure 4 displays the socket prevalence of each blast, determined using Equation (1). All panels observed at Shaft A were mined on strike, except for Panel 3, which was mined up-dip.

Figure 5 compares the results of the planned and actual advance per blast at Shaft B, and the socket prevalence results for each blast are shown in Figure 6. All observed panels at Shaft B were mined on strike.

4.2. Powder Factor

The results of the powder factor for Blasts 1 to 20 at Shaft A are shown in Figure 7. The target powder factor varied from 1.30 kg/m³ to 2.24 kg/m³ based on the actual panel geometry and general conditions post-barring. The variation in the actual powder factor

between blasts was due to the changes in the panel width and length, the number of blastholes drilled and charged, and the number of explosives pumped per blasthole.

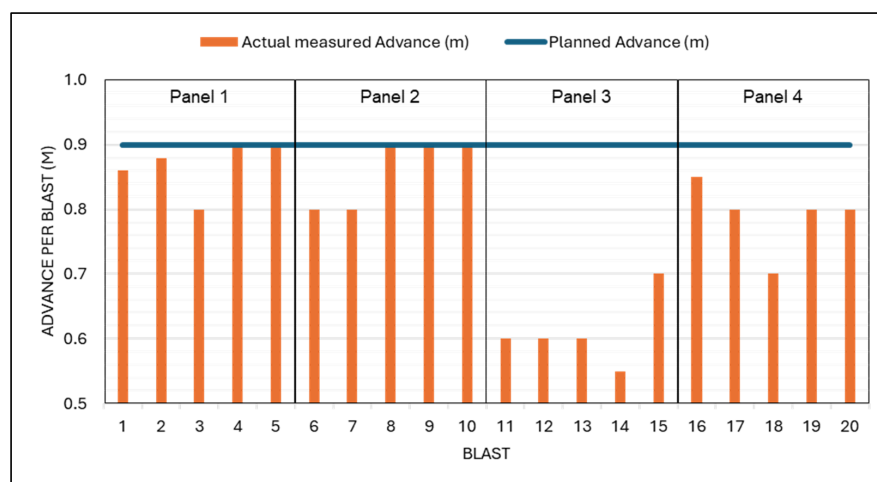


Figure 3. The planned advance per blast based on the blasthole length drilled versus the average actual advance per blast measured at Shaft A when using pumpable emulsion explosives [14].

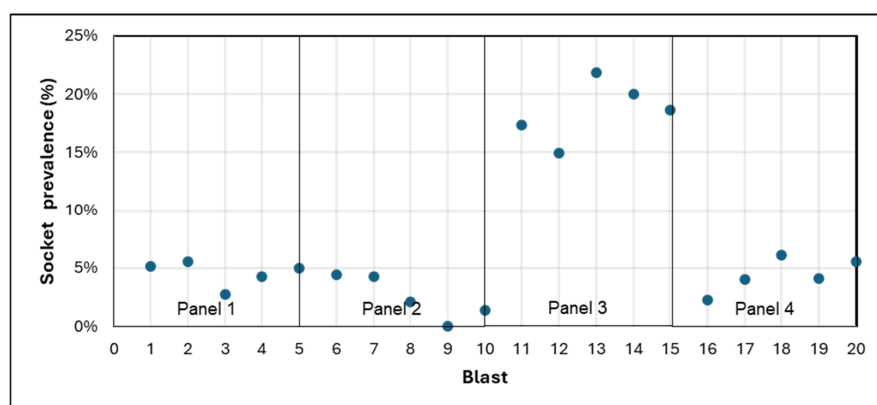


Figure 4. The average socket prevalence per blast observed at Shaft A when using pumpable emulsion explosives [14].

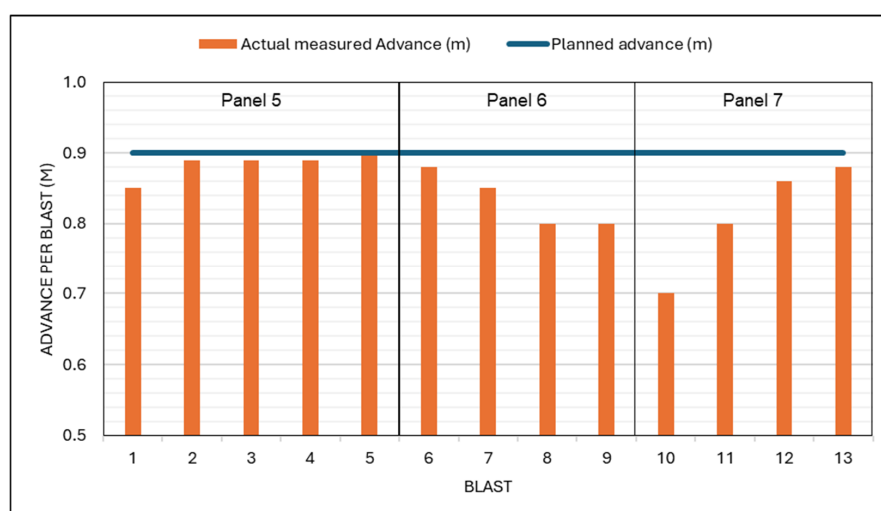


Figure 5. The planned advance per blast based on the blasthole length drilled versus the average actual advance per blast measured at Shaft B when using pumpable emulsion explosives [14].

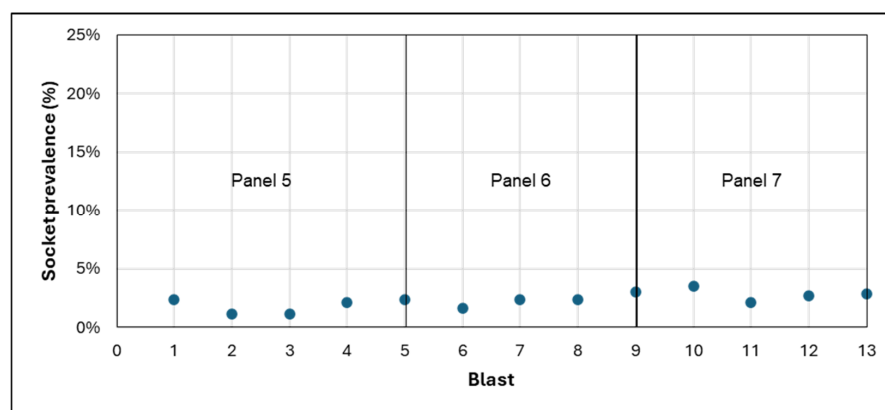


Figure 6. The average socket prevalence per blast observed at Shaft B when using pumpable emulsion explosives [14].

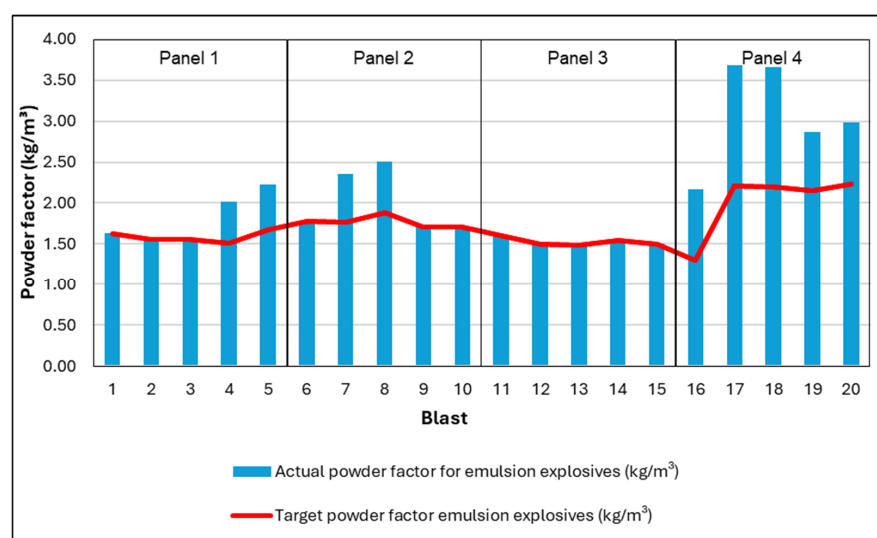


Figure 7. The target and actual powder factors for pumpable emulsion explosives at Shaft A [14].

The results of the powder factor for Blasts 1 to 13 at Shaft B are shown in Figure 8. Like Shaft A, variation in the stope geometry was observed in Shaft B, which resulted in variations in the target powder factor.

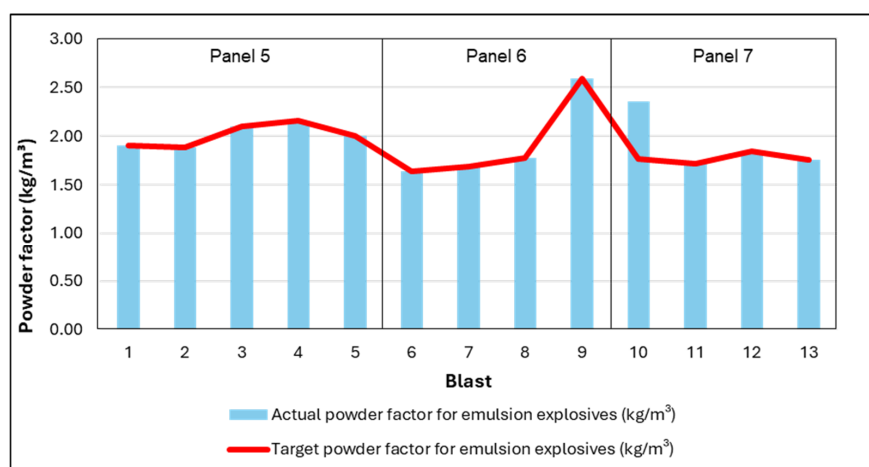


Figure 8. The target and actual powder factors for pumpable emulsion explosives at Shaft B [14].

4.3. Fragmentation

Table 4 shows Shaft A's predicted X_{50} of pumpable emulsion explosives and the results of Split-Desktop and WipFrag software image analyses [14]. The X_{50} of emulsion explosives was predicted using Equation (3), and the actual X_{50} of Split-Desktop and WipFrag software was based on several images of the resulting muck piles. The required X_{50} for Shaft A is between 11.5 cm and 13.5 cm. Figure 9 compares the predicted X_{50} , to that obtained using Split-Desktop and WipFrag.

Table 4. The average Shaft A's predicted X_{50} of pumpable emulsion based on the actual charge and the X_{50} results from Split-Desktop and WipFrag software image analyses.

Location	Predicted Emulsion X_{50} (cm)	Emulsion X_{50} of Split-Desktop Image Analysis (cm)	Emulsion X_{50} of WipFrag Image Analysis (cm)	Shaft A's Target X_{50} Range Post-Blast (cm)
Panel 1: Blast 3	7.18	7.48	14.1	11.5–13.5
Panel 2: Blast 7	6.16	5.73	13.63	11.5–13.5
Panel 3: Blast 15	7.55	3.58	12.84	11.5–13.5
Panel 4: Blast 18	4.24	5.94	12.81	11.5–13.5

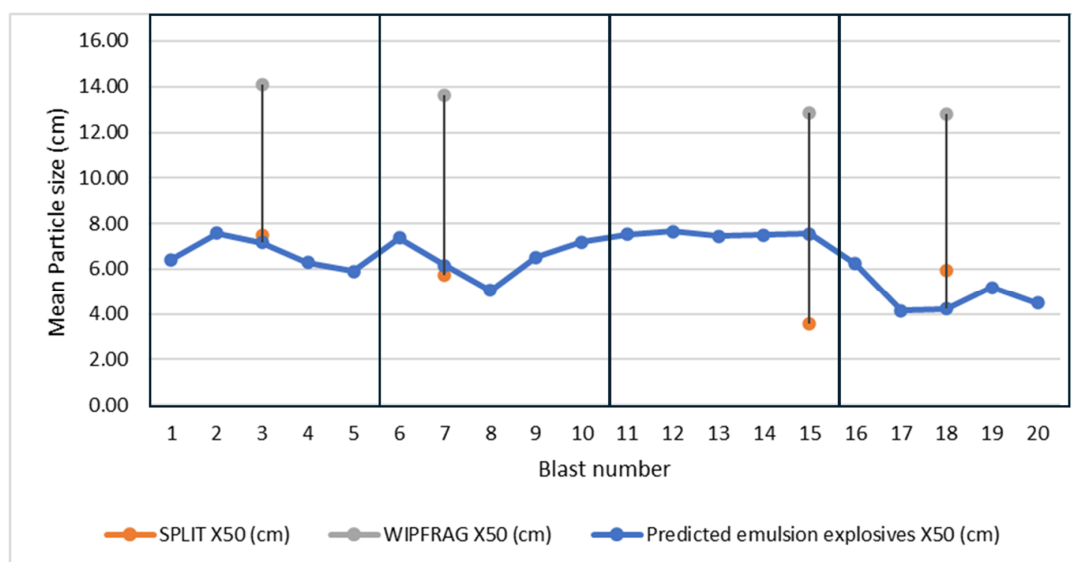


Figure 9. The X_{50} of images analysed through Split-Desktop software and the predicted X_{50} from the Kuznetsov Equation at Shaft A [14].

Table 5 shows Shaft B's predicted X_{50} of pumpable emulsion explosives and the results of Split-Desktop and WipFrag software image analyses [14]. In Table 5 and Figure 10, it can be observed that the WipFrag X_{50} in Blast 3 is within the mine's target range, in Blast 6 is marginal, and in Blast 13 is below the range, but the Split-Desktop X_{50} for all blasts is below this range.

Table 5. The average Shaft B's predicted X_{50} of pumpable emulsion based on the actual charge and the X_{50} results in Split-Desktop and WipFrag software image analyses.

Location	Predicted Emulsion X_{50} (cm)	Emulsion X_{50} of Split-Desktop Image Analysis (cm)	Emulsion X_{50} of WipFrag Image Analysis (cm)	Shaft B's Target X_{50} Range Post-Blast (cm)
Panel 5: Blast 3	5.73	5.08	11.69	11.5–13.5
Panel 6: Blast 6	8.48	8.49	11.31	11.5–13.5
Panel 7: Blast 13	7.11	8.63	9.73	11.5–13.5

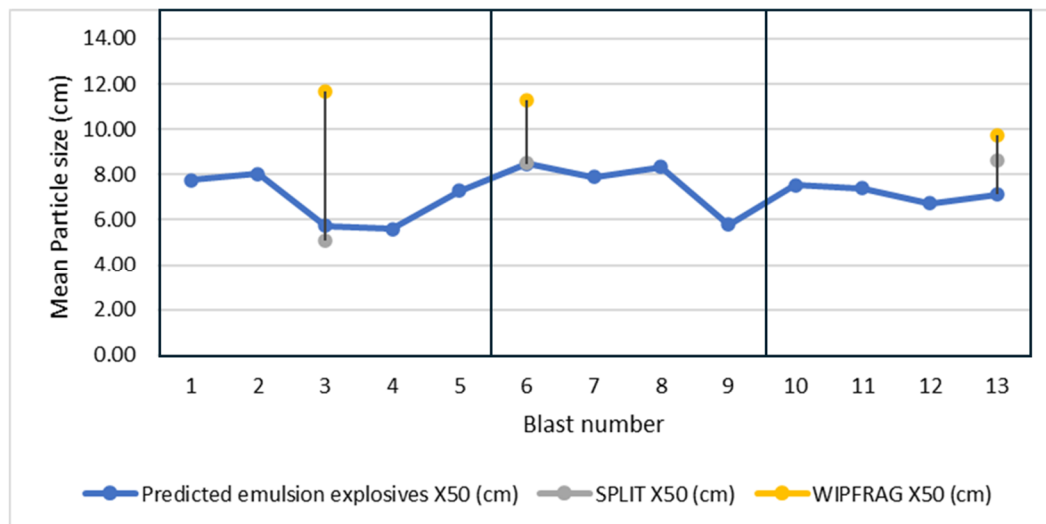


Figure 10. The X_{50} of images analysed through Split-Desktop software and predicted X_{50} from the Kuznetsov Equation at Shaft B [14].

5. Discussion

5.1. Face Advance

5.1.1. Face Advance at Shaft A

As shown in Figure 3, the face advance achieved over the 20 blasts observed are variable. The face advance for Panel 1 in Blasts 1 and 2 was 86 cm and 88 cm, respectively, while Blast 3 just achieved the minimum acceptable face advance of 80 cm. Blasts 4 and 5 achieved the maximum required advance of 90 cm. The average socket prevalence of Panel 1 in Figure 4 was 4.6%, which was lower than the 10% threshold. Blast 3 has the lowest socket prevalence at 3%, indicating that the average length of the blastholes drilled was less than the required 90 cm.

The results of Blasts 6 to 10 in Panel 2 were, in general, better than those of Blasts 1 to 5 in Panel 1. The face advance achieved in Blasts 6 and 7 was the minimum expected advance per blast of 80 cm, while Blasts 7, 8, and 9 achieved the maximum required face advance of 90 cm. The average socket prevalence of all five blasts in Panel 2 was 2.2%, and this can be classified as good.

Blasts 11 to 15 in Figure 3 were carried out in Panel 3. The outcomes of these blasts were characterised by a poor face advance per blast and a high socket prevalence in all blasts. This is because Panel 3 involved mining up-dip at an apparent dip of 22°, indicating the possibility of emulsion slumping from the toe towards the collar of the blastholes. For Blasts 11 to 13, the face advance was 60 cm, Blast 14 achieved a face advance of 55 cm, and for Blast 15, it was 70 cm. As shown in Figure 4, the average socket prevalence in Panel 3 was 18.6%, with the highest peaking at 22% in Blast 13, recording the longest socket length of 50 cm, with an average socket length of 30 cm. Although Blast 14 achieved the smallest face advance, it had the second-highest socket prevalence. The high socket prevalence in Blast 13 was compounded by fewer blastholes drilled (64) compared to Blast 14 (75).

Blasts 16 to 20 took place in Panel 4. The average advance per blast of all five blasts was 81 cm, with Blast 18 having a lower advance per blast of 70 cm due to poor emulsion gassing, as the pump of the portable charging unit (PCU) was not functioning optimally. In all five blasts in Panel 4, the average socket prevalence was less than 10%, with the highest socket prevalence being 7% in Blast 18, with corresponding sockets of up to 20 cm.

5.1.2. Face Advance at Shaft B

Blasts 1 to 5 in Figure 5 took place in Panel 5 at Shaft B. The planned advance per blast range was 80 cm to 90 cm, while an advance per blast of 85 cm, 89 cm, and 90 cm was achieved in Blast 1, Blasts 2 to 4, and Blast 5, respectively. The average socket prevalence for all five blasts in Panel 5 in Figure 6 was 1.6%.

Blasts 6 to 9 in Figure 6 took place in Panel 6. Blast 6 had an advance per blast of 88 cm, and that of Blast 7 was 87 cm, whereas Blasts 8 and 9 had an advance per blast of 80 cm each. The average socket prevalence for all blasts was below 4%, indicating overall acceptable blast results.

Blasts 10 to 13 took place in Panel 7. The best advance per blast achieved was 88 cm in Blast 13, with the lowest advance in Blast 10 at 70 cm. It was observed in Blast 10 that the drilling angle in the middle blastholes was between 70° to 80° to the horizontal plane. Overall, the socket prevalence was below the benchmark of 10%.

5.1.3. Overall Analysis of Face Advance

The overall analysis of the results from both shafts points to emulsion explosives being capable of achieving the minimum required face advance of 90% of the blasthole length in narrow-reef mining under normal operating conditions. At Shaft A, 14 out of 20 observed blasts achieved a face advance within the acceptable range of between 80 cm and 90 cm. At Shaft B, 12 out of 13 observed blasts also achieved a face advance within the acceptable range. The general socket prevalence of less than 4% at Shaft B is another indication of the capability of emulsion explosives to achieve the required face advance.

Panel 3 at Shaft A experienced a socket prevalence above the 10% limit due to up-dip mining. The emulsion used was a non-sticky compound meant to be used in horizontal or down-holes. Up-dip mining can result in the emulsion slumping towards the collar from the toe of the blasthole, reducing the powder factor at the toe of the blasthole, thus leaving the toe with an insufficient product to break the rock.

The execution of the blast geometry on the spacing, drilling direction, and drilled hole length is often an issue; however, the mine supervisors continuously perform regular audits during marking and drilling activities to identify the teams' shortfalls and provide coaching. Shafts A and B also employ "stope observers" who measure the teams' drilling accuracy and generate a report for mine management. In addition, the two shafts offer financial incentives to teams that achieve the set monthly face advance target. In general, the level of discipline among drillers at Shaft B was higher than in Shaft A, probably due to partings in the hanging wall and the consequent susceptibility to overbreaking.

A face advance is an important key performance indicator in narrow-reef mining. The results of the face advance analysis support the assertion that the ability of pumpable emulsion explosives to provide full coupling can increase the energy at the blasthole toe [7], thereby increasing the face advance.

5.2. Powder Factor

5.2.1. Powder Factor at Shaft A

Figure 7 shows the powder factor results for Panels 1 to 4 at Shaft A. The PCU used at the mine is configured to pump 0.2 kg of emulsion explosives per stroke, and each blasthole takes three strokes to achieve the required charge length. The actual powder factor for pumpable emulsion explosives was based on the number of explosives pumped into each blasthole, which was estimated using Equation (2).

The analyses of the powder factor in Panel 1 show that the actual powder factor in Blasts 4 and 5 was significantly higher than the target powder factor. This is because some

of the blastholes in Blasts 4 and 5 were charged with an additional 0.2 kg of explosives, thereby increasing the actual powder factor.

The results for Panel 2 at Shaft A are shown in Figure 7, where Blasts 6 to 10 were conducted. Blasts 7 and 8 had a higher actual powder factor due to an additional 0.2 kg above the planned 0.6 kg being pumped into some blastholes. On the other hand, the actual powder factor in Blasts 6, 9, and 10 was equal to the target powder factor.

Blasts 11 to 15 were conducted in Panel 3. The actual powder factor for emulsion explosives was equal to the target powder factor. It was observed that due to the challenging drilling conditions, two rows of blastholes were drilled instead of the required three rows, with random additional blastholes drilled in between to make up for the missing row.

Blasts 16 to 20 were carried out in Panel 4, and all four blasts had a higher actual powder factor than the target powder factors. The mass of explosives per hole was between four and five strokes instead of the planned three strokes. Panel 4 was initially blasted with two rows of blastholes in Blast 16 but increased to three rows for Blasts 17 to 20. This may explain the significant increase in the actual powder factor in these blasts.

5.2.2. Powder Factor at Shaft B

The actual powder factor for all panel blasts at Shaft B was equal to the target powder factor, except for Blast 10. This was due to the overcharging of some blastholes by 0.2 kg above the planned 0.6 kg. Again, the adherence to the planned powder factor at Shaft B points to the level of discipline in this shaft compared to Shaft A.

5.2.3. Overall Analysis of Powder Factor

There is a high chance that the powder factor of pumpable emulsion explosives can deviate from the plan in narrow-reef mining due to three main factors:

- A decrease in the mass of the explosives due to two rows of blastholes being drilled instead of the prescribed three rows in some panels, which will result in a low powder factor;
- An increase in the mass of the explosives per blasthole due to the pumping of four or five strokes of explosive instead of the required three strokes by some crews, which will result in a high powder factor;
- An increase in the mass of the explosives per blast due to an increase in the number of holes because of the on-the-face drill pattern adjustment. Because of the nature of the emulsion explosives in relation to cartridge explosives, there is a high likelihood of overcharging and wastage underground. Therefore, charging with emulsion requires training, discipline, and supervision.

5.3. Fragmentation

During fragmentation analysis, the muck pile of one blast per panel was analysed to minimise production stoppages. Both Shafts A and B use WipFrag to analyse the fragmentation, and we used Split-Desktop for validation. It can be observed in Table 4 that according to the WipFrag, the X_{50} of Blasts 3 and 7 is beyond the range and that of Blasts 15 and 18 is within the target range. However, the WipFrag X_{50} of all blasts is significantly above the predicted X_{50} based on Equation (3) (Kuznetsov Equation). The difference can be attributed to the Kuznetsov Equation's tendency to overestimate the fines fractions of a blast [15,16]. In Table 4 and Figure 9, the predicted X_{50} is close to the Split-Desktop X_{50} .

In Figure 9, the predicted X_{50} for all 20 blasts was variable due to the adjustments that the section supervisors (miners) made because of the changes on the face. In Figure 9, the Split-Desktop X_{50} of Blasts 3 and 7 are close to the predicted X_{50} of the respective blasts. However, there are significant differences for Blasts 15 and 18. In the case of Blast 15, this

could be due to Panel 3 being mined up-dip, resulting in the concentration of explosive energy at the collar region of the blastholes. This caused finer fragmentation and long sockets, as observed in Figure 4. In Blast 18, as mentioned earlier, more explosives per blasthole were charged than planned, resulting in inadequate stemming lengths, which did not provide enough explosion confinement. There could also be the issue of an incorrect amount of gassing agent mixed with the emulsion, as the PCU was not operating normally. Nonetheless, the Split-Desktop X_{50} and the predicted X_{50} were below the shaft's expected range of 11.5 cm to 13.5 cm.

Figure 10 shows the predicted X_{50} , Split-Desktop X_{50} , and WipFrag X_{50} of muck piles in Panels 5, 6, and 7 at Shaft B. The WipFrag X_{50} results are close to the shaft's target range and well above the predicted X_{50} . The Split-Desktop X_{50} results are close to the predicted X_{50} and below the expected shaft target range of 11.5 cm to 13.5 cm.

In both shafts, the predicted X_{50} was based on the resulting stope geometry and conditions after barring. In all 33 observations, the predicted X_{50} was below the target range. The latter was close to the Split-Desktop X_{50} compared to WipFrag X_{50} , which, in turn, was largely within the expected target range of both shafts. The difference between the X_{50} of Split-Desktop and WipFrag leads us to not conclude whether emulsion explosives in narrow-reef stopes can result in the required fragmentation of between 11.5 cm and 13.5 cm. However, it is noted that the Kuznetsov Equation tends to overestimate the fines fractions of a blast, and this cautiously points to the probability that the WipFrag X_{50} could be a true reflection.

6. Conclusions

This paper presented the results of pumpable emulsion explosive performance based on three key performance indicators—namely face advance, powder factor, and fragmentation—in narrow-reef stopes. The results show that emulsion explosives can enhance the ability of a mine to achieve a target face advance with associated low socket prevalence. However, the direction of mining appears to be a factor when using pumpable emulsion explosives. For example, when mining up-dip, as was the case with Panel 3, the emulsion tends to slump towards the collar, presumably due to improper stemming and no stemming at all, thereby resulting in long sockets and a poor face advance. It can, therefore, be pointed out that the pumpable emulsion is suitable for on-strike mining and possibly down-dip mining in narrow-reef mining.

Narrow-reef mining, due to the sheer number of people involved in stoping activities and the low level of mechanisation, requires discipline and supervision. There were several incidents observed where charging crews overcharged the blastholes with additional one or two strokes, particularly in Shaft A. On the other hand, if controls are in place, as was the case with Shaft B, the likelihood of using the correct quantity of explosives will be high.

Lastly, the fragmentation results of the pumpable emulsion in our investigation, using X_{50} as a KPI, are inconclusive. In our case, the Wipfrag X_{50} was close to both shafts' X_{50} 's target range, while the Split-Desktop X_{50} was more in line with the Kuznetsov Equation prediction. In this regard, we would recommend that fragmentation distribution analysis be conducted to determine if pumpable emulsion explosives can achieve the required fragmentation in narrow-reef mining.

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