School of Mining Engineering

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

QUANTIFICATION OF THE BENEFITS OF PUMPABLE EMULSION EXPLOSIVES IN NARROW REEF GOLD MINES

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ABSTRACT

Pumpable emulsion explosives usage is gaining ground in South African underground narrow reef mining following its wide application on the surface and underground massive mining. Following the advancement in the narrow reef, this research sought to quantify the benefits of pumpable emulsion explosives in narrow reef stopes of gold mines under non-trial conditions on three key performance areas (KPA) of cost of explosives, blasting efficiency and post-blast conditions.

The study adopted both qualitative and quantitative methodological approaches where historical and primary data was collected at the identified underground shafts of Ya Rona and Hlanganani. Historical data included planned targets and achieved results before and after the introduction of pumpable emulsion explosives at the shafts. The primary data was gathered through a total of 33 underground observations at the two shafts.

The analysis of three KPAs was done through corresponding KPIs of explosives cost, face advance, powder factor, fragmentation distribution, and hangingwall overbreak. The cost of explosives KPA analysis indicated that pumpable emulsion was cost-effective when compared to cartridge explosives and the planned target. The blasting efficiency KPA was analysed through three KPIs, namely, face advance, powder factor, and fragmentation. The primary data analysis showed that the pumpable emulsion explosives were capable of achieving the mine's required face advance at both shafts, and the historical data analysis showed that pumpable emulsion explosives performed better at the Ya Rona shaft and poorly at the Hlanganani shaft. The pumpable emulsion explosives powder factor calculated from the underground measurements can be lower or higher than the corresponding planned powder factor due to in-situ site conditions. Blast fragmentation analysed images showed that pumpable emulsion explosives can achieve the mine expected range fragmentation size or be below as indicated by the two image analysis programmes used and the Kuz-Ram estimation. Post-blast conditions were analysed using the hangingwall overbreak which cautiously showed that emulsion explosives have the potential to negatively impact the panel's post-blast condition due to non-adherence to the blast design parameters and the influence of the geological conditions.

The research KPAs of cost of explosives, blasting efficiency and post blast conditions through the respective KPIs have indicated that emulsion explosives could achieve blast outcomes that were within the mine target. The analysis of the cost of explosives, face advance and powder factor KPIs conclusively showed the positive outcome pumpable emulsion explosives could have in narrow reef mines; though the powder factor showed dependence on other factors. The analysis of hangingwall overbreak KPI revealed a possible negative impact, while the analysis of the fragmentation KPI yielded an inconclusive outcome. Based on the results, the study proved the effectiveness of pumpable emulsion in narrow reef stope mining under non-trial operational conditions. It also quantified the benefits of pumpable emulsion explosives in narrow reef gold mines.

Notwithstanding, it is recommended that further research on fragmentation analysis using different analysis methods and more research on the extent of the hangingwall damage when pumpable emulsion explosives are used should be conducted.

Keywords:

Pumpable emulsion explosives; Cartridge explosives; Explosives cost; Face advance; Powder factor; Fragmentation distribution; and Hangingwall overbreak.

DEDICATION

I dedicate this report to the memory of my father Nelson Pheladi Mabapa Choshi, who supported me throughout my academic journey. I am grateful for the countless sacrifices he made to provide me with the opportunities that have brought me to where I am today. I also dedicate this to my son Lethabo Amukelo Choshi, and I hope that he will be inspired to pursue his dreams and never give up on what he believes in.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

APPENDIX LIST OF TABLES

LIST OF EQUATIONS

ABBREVIATIONS

ANFO	Ammonium nitrate–fuel oil
CLR	Carbon Leader Reef
KPA	Key Performance Areas
KPI	Key Performance Indicators
MCU	Mobile Charging Unit
PCU	Portable Charging Unit
RBS	Relative Bulk Strength
RWS	Relative Weight Strength
SW	Stope Width
VCR	Ventersdorp Contact Reef
VOD	Velocity of Detonation

UNITS OF MEASUREMENT

cm	Centimetre
ℓ	Litre
kg	Kilograms
kg/m^3	Kilogram per cubic metre
m	Metre
mm	Millimetre
MPa	Megapascals
t	Tonnage
R/m^2	Rand per square metre
%	Percentage

1 INTRODUCTION

1.1 Introduction

The report outlines a research study conducted on quantification of the benefits of pumpable emulsion explosives usage in underground narrow reef gold mines in South Africa. The study was conducted at two underground narrow reef gold mines in the Witwatersrand basin, namely Ya Rona shaft and Hlanganani shaft.

The use of pumpable emulsion explosives is gaining ground in the underground narrow reef mining market due to technological advancement in the equipment required for the charging-up process. Two South African mining companies which owns deep level gold mines have adopted pumpable emulsion explosives at some of their narrow reef underground mines in the past five years, with some shafts being fully converted to emulsion explosives in the stopes and other shafts using both cartridge explosives and emulsion in the stopes. There is obviously a varying degree of successes and failures at various shafts since the use emulsion explosives. The quantification of the benefits of pumpable emulsion explosives in narrow reef stopes envisaged in this study will assist the mines in selecting the correct explosives.

1.2 Purpose of this study

Blasting is a fundamental and significant mining activity that provides the most economical and flexible means of extracting ore from the orebody in a hard rock mine (Sellers, 2011). The use of explosives has direct influence on production and safety of the operation, which can either negatively or positively impact the mine’s finance (Busuyi, 2009). Blasting is also a strategic activity in a mine operation, as it has influence on downstream activities and affects the overall performance of both the mine and the explosives supplier.

The pumpable emulsion explosives are a push innovation that was introduced in underground narrow reef mining to improve safety, reliability and blast performance (Pearton, 2015). The underground narrow reef mining market is experiencing a rise in the use of pumpable emulsion explosives. Following these advances, it is crucial to be able to accurately review and measure overall performance and conversion to pumpable emulsion explosives using key performance areas (KPA).

KPAs are valuable tools for monitoring and managing performance in areas that are strategic to organisational or operational goals that show critical success drivers of the company (Dougall and Mmola, 2015). They can be monitored through the establishment of appropriate key performance indicators (KPI), which represent performance metrics to measure the success of the chosen activity or aspect (Cardu et al., 2015). It is in this context that this research seeks to prove the efficacy of pumpable emulsion in narrow reef stope mining under non-trial operational conditions and also provide unbiased evidence.

1.3 Research background

South African underground gold mining production has been on a decline due to technical, financial, human resource, and policy challenges. The challenges impacting on productivity in the deep level gold mines include the escalating cost of production, gold price volatility, declining gold resource grade, depth, labour issues, political, social, and environmental issues (Neingo and Tholana, 2016).

These challenges essentially affect mine production as well as operational efficiency and goals. The integration of technology, collaboration and partnership between suppliers and mining companies is crucial in maximising productivity in narrow reef mines and holds solutions to restore their competitiveness (Willis et al., 2004).

The introduction of pumpable emulsion explosives in underground conventional narrow reef stopes is seen as a possible technological solution to operational challenges that affect productivity, costs, and safety. Pumpable emulsion explosives are widely applied in surface and underground massive mines, with minimal use in underground narrow reef mines due to high costs, logistics complexities, unavailability of appropriate charging equipment, and limited research and data about its application in 36 mm and less diameter blastholes typically used in narrow reef mining (Pearton, 2014; 2015).

Pearton (2015) compared the pumpable emulsion explosives with existing cartridge explosives, focusing on blasting efficiencies such as production output, explosives costs and blast results. The variables related to the blast results such as fragmentation and advance per blast were identified during the field tests as areas that require more tests to determine the long-term influence from the use of pumpable emulsion explosives.

The practical and economic benefits of using pumpable emulsion explosives may influence the technical decision to select pumpable emulsion as an explosive of choice. The decision is further influenced by the suppliers’ services and pricing during the contracts negotiations (Thompson, 2004; Bennett and Parsons, 2007). The long-term benefits of the selected explosives option have to be apparent and measured against operational goals such as costs containment, production and safety, and the benefits must translate into quantifiable improvements.

1.4 Research motivation

Narrow reef gold mines recognise the need to successfully implement new technologies and innovative methods to remain competitive and counter cost upswings and declining profit margins of mines (Macfarlane, 2001). The introduction of pumpable emulsion explosives in underground narrow reef stope mines brings technological change that impacts on the blasting activity.

Traditionally, mines evaluate explosives' performance on costs, with less attention given to other non-financial factors or explosives benefits. Harmony Gold and Sibanye-Stillwater Gold Division have adopted pumpable emulsion explosives at some of their narrow reef underground mines in the past five years, with some shafts being fully converted to emulsion explosives and others using both cartridge and emulsion explosives in the stopes. Amongst the converted shafts, some are satisfied with the use of emulsion explosives, whereas others have raised issues with regard to increase in cost of explosives and not achieving anticipated production benefits. Therefore, this research has sought to quantify the benefits of pumpable emulsion explosives in narrow reef stopes of gold mines on non-trial basis.

1.5 Problem statement

The use of pumpable emulsion explosives in conventional narrow reef stopes is growing; Harmony Gold is in the process of converting all their South African gold operations to pumpable emulsion explosives and Sibanye-Stillwater Gold Division has already converted three operations and is in the process of converting two more operations. With this being the case, there is lack of quantifiable evidence of the benefits of pumpable emulsion explosives in narrow reef stopes, at least beyond the trial phase, compared to the benefits of the same in massive mining and development.

The correct selection and application of explosives helps prevent damage to hangingwall and reduce the exposure of miners to unsafe conditions (Sellers, 2011). However, the lack of publicly available quantifiable evidence reduces the level of confidence in the effectiveness of pumpable emulsion explosives in underground narrow reef stopes during the selection of explosives and leaves the mine management to rely solely on sales pitch of explosives suppliers.

There is a need to blast full drilled length of a blasthole in order to achieve the planned production targets safely and cost effectively. An unattained full daily advance increase explosives costs and reduce blasting efficiency due to repetitive blasting (Pearton, 2014). Therefore, this research set out to quantify the benefits of pumpable emulsion explosives in the narrow reef stopes of gold mines on three fronts; namely explosives cost, blasting efficiency and post-blast conditions. Table 1.1 shows KPAs and corresponding KPIs that were evaluated in this research.

Table 1.1: KPAs and KPIs to be used in the quantification of the benefits of pumpable emulsion explosives at Ya Rona and Hlanganani mines

KPA	Description	KPI (metrics)
Explosives costs	Cost of blasting materials such as initiating systems and emulsion including the gassing component and related costs such as spares and maintenance.	• Explosive cost per square metre of blasted rock (R/m^2)
Blasting efficiency	Propensity to achieve set production factor targets	• Face advance (m) • Powder factor (kg/m^3) • Fragmentation distribution (percentage passing)
Post blast conditions	Post blast conditions induced by blasting	• Hangingwall overbreak (%)

1.6 Research Objectives

The objectives of the research were to:

- Create an understanding of the application of pumpable emulsion explosives in narrow reef stopes of gold mines; and
- Establish whether pumpable emulsion explosives are cost effective compared to cartridge explosives in narrow reef stopes.

1.7 Research Question

Based on the above stated objectives, the resultant research question is:

- What are the actual benefits of pumpable emulsion explosives in narrow reef stopes?

1.8 Report Outline

Chapter 1 introduces and outlines the background on elements that are the bases of this research, the purpose, motivation, question and objectives of this research. It further states the problem statement. Chapter 2 is a literature survey of the subject of this research. It covers the application of pumpable emulsion explosives in underground mining and their benefits, and the selected blasting KPAs of costs, blasting efficiency and post blasting conditions are explained in detail.

Chapter 3 covers the methodology and methods used to achieve the research objectives. The chapter also describes the research sites in terms of the geology and mining methods. This chapter focus on methods used to acquire the primary data. Chapter 4 presents the historical and primary data collected from the mine. This chapter also outlines the targets or industry norms for the selected KPIs. Chapter 4 further covers observations, tabulation, and description of research data.

The primary and historic data collected were analysed in the context of set norms in relation to the corresponding KPIs of blast efficiencies, explosives costs and post-blast conditions in Chapter 5. Chapter 6 concludes the research and provide recommendations.

2 LITERATURE SURVEY

2.1 Introduction

The performance of explosives is generally assessed through technical evaluation and blasting cost. Technical evaluation may include extensive underground trials on explosives' compatibility with local ground conditions, and the assessment of blast outcomes such as fragmentation, hangingwall and footwall damage, and blasting vibration (Gill, 1995 and Juge *et al.,* 2004).

With this view, this chapter covers literature review on the factors that affect blasting outcome in narrow reef mining. The factors covered are blast design consideration in narrow reef mining and the selection of explosives. These two factors are depended on variables such as stope width (SW), blasthole diameter, stemming, burden and spacing, and types of explosives used in narrow reef mining. The literature review was also conducted on the selected blasting KPAs of pumpable emulsion explosives usage in underground mines.

2.2 Blast design consideration in narrow reef stopes

The blast design plays a significant role in the optimal usage of explosives, associated costs of explosives and the final extraction costs of minerals (Gaula, 2015). Improperly designed blast potentially contributes to underground hazardous conditions through reduction of rock mass competency and damage to surrounding roof, walls or support (Iverson, 2007). An adequate blast design assists the mine to achieve required blast outcomes and production, adhere to environmental and operational requirements, and ensures all is done within reasonable costs. The blast design parameters are reliant on rock mass characteristics and correct selection of explosives (Rajpot, 2009). The blast design parameters must be easily adjustable to cater for the geological conditions and take advantage of the released energy of explosives. The stoping width, burden and spacing, blasthole diameter, and stemming are some of the main parameters taken into account in blast designs and are discussed below.

2.2.1 Stope width

The stope width for a panel is controlled by the mine design approach used for ore extraction which is subsequently influenced by the ore characteristics of the targeted reef, the cut-off grade and the geological model (Birch, 2017). In essence, the nature of the reef dictates the planned stope width. Mines often have standardised marking for drilling patterns. For example, in gold mines in South Africa if the stope width is greater than 150 cm, three rows are generally marked for drilling and if smaller than 150 cm, then two rows are generally marked. In the narrow reefs of gold mines in South Africa, marking is generally 25 cm from hangingwall and 35 cm from the footwall. The variation in the stope width affects the number of rows to be drilled, which in turn affects the spacing between the blastholes, while burden is unchanged (Sibanye Stillwater Standard, 2020).

2.2.2 Burden and spacing

The spacing and burden blast design parameters are often defined by their ratio, that is, the spacing to burden ratio. The two parameters are related, therefore an adjustment of one parameter without considering the other may result in an inadequate use of the explosives energy. The spacing to burden ratio has direct effect on the blast outcomes such as fragmentation and overbreak or under-break (Singh and Abdul, 2012). Breaking maximum burdens holds potential value for the mine in terms of explosives consumption and blast outcome. Figure 2.1 shows a typical blast design in narrow reef mining with two rows drilled.

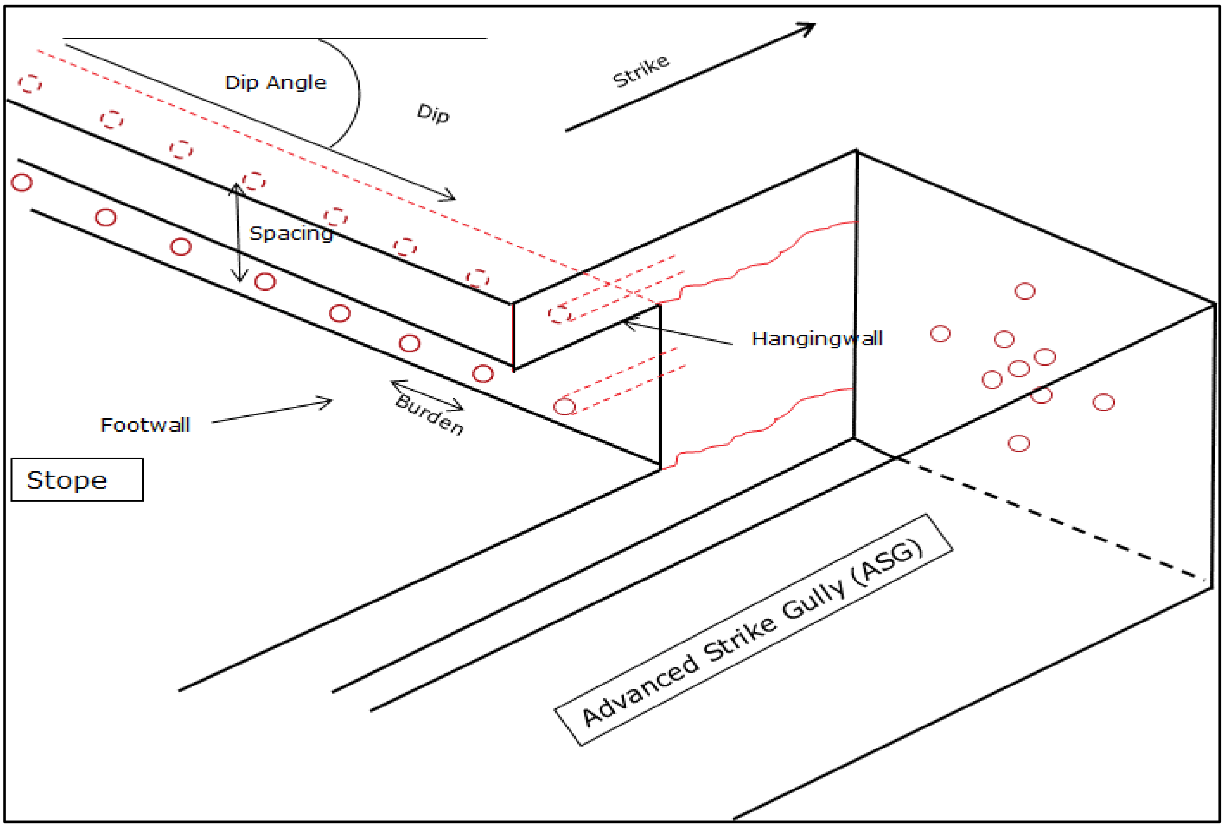

Figure 2.1: Example of underground narrow reef stope (AECI Mining Explosives, 2018a)

The maximum effective burden results in the reduction of blastholes per panel, explosives and initiating systems usage, and drilling and charging times. Cunningham et al., 2002 in the threshold blasting trials, demonstrated that the use of pumpable emulsion explosives has the potential to reduce drilling cost through the use of minimum amount of explosives required to fragment a rock and therefore the cost of production provided minimal number of blastholes are drilled and charged.

2.2.3 Blasthole diameter

The blasthole diameter is one of the blast design parameter that has got a direct impact on the blast outcome due to its role in the distribution of explosives in a blast. The cost of drilling and blasting depends on the blastholes diameter, rock mass properties, and required blast outcome such as fragmentation (Rajpot, 2009). According to Singh and Abdul (2012), the mean particle size increases with the increase in burden to blastholes diameter ratio. The effective charge mass increases with the increase in blasthole diameter (COMRO, 1989).

However, blasthole diameter increase has to be balanced with possible impact of blast on the hangingwall in narrow reef as the degree of damage commensurate with the amount of explosive charge used in the blast round (Iverson, 2007). Figure 2.2 compares the extent of the blast damage to the break limit, which is described as the maximum distance to where the blast round successfully fragments the rock.

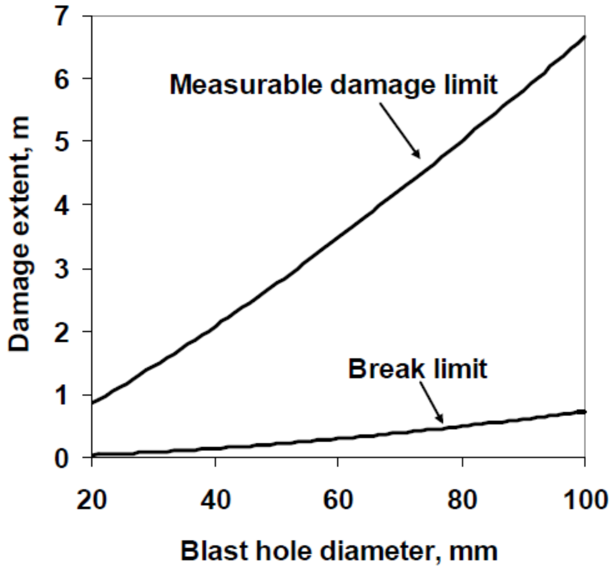

Figure 2.2: Approximate damage zone extent for fully coupled blastholes calculated from Holmberg-Persson equation using critical PPV values for each damage type (Iverson, 2007)

Figure 2.2 depicts the approximated damage zone extent for fully coupled blastholes for different blasthole diameters, which are applicable in underground mining. The full or 100% coupling is achieved through charging of the blasthole with pumpable explosives where a hose is inserted to the toe of the blasthole and the pumped explosives fills the blasthole to the desired charge length as the hose retract out of the blasthole. In contrary, cartridge explosives achieve coupling ratio of 60 to 70% of the blasthole volume. Completely filling the hole provides much greater energy for breakage (Bennett and Parsons, 2007). Decoupled charges are in perimeter holes to eliminate or control overbreak (Iverson, 2007).

2.2.4 Stemming

Stemming has positive impact on the blasting performance, especially fragmentation and burden movement. The useful explosives gas energy gets retained in the blasthole and interact with the rock mass when stemming is used in high Velocity of Detonation (VOD) explosives such as emulsion explosives. The explosives with higher VOD are considered to have high shock energy content, therefore stemming assist in retaining the gas energy as compared to unstemmed holes where the energy would be ejected through the blasthole collar. The stemming maximise the period in which high pressure gases remain with the rock mass to act on the burden and increasing overall efficiency (Pearton, 2014).

The low VOD has higher form of gas energy and release its energy at a slower rate (Cameron and Grouhel, 1990). The contributions of shock and gas energy differ based on the hardness of the rock, the type of explosives and containment of explosives. Gas energy play a significant role in fragmentation process by increasing the length of the cracks generated by the shock energy by a factor of five to ten, with stemming improving the maximum crack radius. Apart from useful shock energy and gas energy; there is also waste energy post detonation which appears in the form of seismic energy, noise, heat, and light. Approximately 40% to 60% of the total explosive energy manifests as waste energy (Oates and Spiteri, 2021).

Stemming is significant as it helps in confining useful energy within the blasthole, which help improves drilling in areas where pre-conditioning has been applied (Sellers, 2011). Drilling is improved in the pre-fractured ground created by pre-conditioning as compared to the virgin ground. The overall efficiency is increased due to the complete breakout of the toe of the blasthole and improvement in fragmentation results through energy utilisation. Due to increased efficiency, smaller quantities of explosives can be used to achieve the optimised blasting outcome (Pearton, 2014; Oates and Spiteri, 2021). The use of stemming significantly improves the efficiency of any type of explosives being used for blasting, more so on the explosives with higher velocity of detonation such as emulsion explosives (Oates and Spiteri, 2021).

2.3 Selection of explosives

The method of selecting explosives often compares different explosive types on practicality, technical application, and financial factors. Sometimes factors such as service agreements and price dominate explosives supplier negotiations, making it harder for the mines without explosive specialists to evaluate and differentiate between explosives suppliers on technical grounds (Juge *et al.,* 2004). The technical selection process requires a clear understanding of explosives' characteristics, rock mass properties and desired blast outcome (Lund and Adamson, 2001). The technically driven negotiation approach is still important to the mining industry because it specify the characteristics of the explosives required to maximise the financial performance of their operations (Juge *et al.*, 2004).

The correct selection of explosive by means of monitoring explosive performance can lead to enhanced safety, increased productivity, and reduction of costs. Apart from costs and performance compatibility with local conditions, the evaluation process for explosives may include ease of use, reliability of supply, technical support and historical relationship with the supplier of explosives (Gill, 1995).

2.3.1 Types of explosives used in deep level gold mines

The explosives manufactures offers a range of ammonia-based explosives products for the South African underground mining market. Geological conditions, environmental application, required blast outcome, physical properties and performance of explosives are critical when selecting explosives but so is the considerations of overbreak, hangingwall damage and concussion (COMRO, 1989). The explosives that are commonly used in the underground narrow reef stopes are cartridge/packaged explosives.

Cartridge explosives

The cartridge or packaged explosives are widely used in the underground narrow reef operations. Different diameters and lengths are supplied for different applications such as production stopes, development ends and priming in larger blastholes development where Ammonium nitrate–fuel oil (ANFO) is used. The explosives are packaged into plastic sleeves of variable dimensions, and leads to less coupling in the blasthole. The formulation of packaged explosives differ with manufactures but the VoD is generally lower than that of pumpable emulsion explosives (Pearton, 2014).

The common packaged explosives used in the stopes are characterised by their length of between 25 cm to 32 cm and diameter of between 25 mm to 32 mm to fit in the drilled blastholes. The packaged explosives are able to be initiated with a 6D strength detonator inserte into a cartridge or by wrapping a 5 g/m detonating cord around them.

The cartridge explosives contemplated in this research (see Table 4.1) are watergel based which consist of solid ammonium nitrate particles suspended in a liquid ammonium nitrate solution, gelled using cross-linking agents. Watergel explosives have lower VOD as compared to pumpable emulsion explosives. Low VOD explosives exhibit lower shock energy compared to higher VOD explosives and cause less fracturing of the rock mass. However, the low VOD explosives have a higher proportion of gas energy because of the slow pressure build up in the blasthole (Pearton, 2014).

Pumpable emulsion explosives

The pumpable emulsion explosives for underground application are an opaque grease-like substance loaded into blastholes using specialised pump delivery system (Juge, Waldock and Scott, 2004). The pumpable emulsion explosives used in short-hole and long-hole blasting have different characteristics suited for each application. The base emulsion and the sensitising agents are stored separately on the Portable Charging Unit (PCU) or Mobile Charging Unit (MCU) and only become explosives when mixed through a homogenizer/static mixer during charging of the blasthole (Das, Sadhwani and Bhaduri, n.d.).

AECI Mining Explosives is currently the sole supplier of bagged pumpable emulsion explosives for use in the narrow reef stopes and are supplied in 25 kg bags with two sub bags of 12.5 kg inside and a sensitiser in 2 ℓ bottles. The sensitised emulsion will adopt the colour of the dye that was added as verification that the product was dosed with a sensitising agent (AEL., 2018). The sensitising agent variety allows emulsion densities to be varied to suit different blasting application. The density of explosives can influence blasting outcome, therefore the selection of the appropriate sensitiser is crucial.

2.4 Blasting KPAs for pumpable emulsion explosives

Safety, costs, product quality, fleet management and delivery were identified as KPAs that should form the basis of any performance monitoring and measurement system on a surface mining operation by Dougall and Mmola (2015). Although underground mines faces different challenges to surface mines, safety, costs, product quality, and delivery are relevant to all mining operations. KPAs are measured through carefully selected KPI metrics (Cardu et al., 2015). The selected KPAs of cost, blasting efficiency and post-blast conditions influence the criteria used when selecting explosives and link blasting activity to the overall business objectives, inclusive of finance, production and safety (Gill, 1995). In addition, blasting performance is directly related to the characteristics and efficiency of the explosives used (Cameron and Grouhel, 1990).

2.4.1 Costs

The overall direct cost assessment of blasting include drilling costs, blasting material costs, and additional costs of blasting operations (Zarghami et al., 2018). The direct costs of explosives per blasthole includes the cost of initiating system, explosives, and pump ownership. The metric used to measure the cost in this research is the South African rand per square metre (R/m^2). The cost in R/m^2 of the pump takes into account the total mass of explosives (kg) pumped over its life to break a given centares (m^2) of ground (Pearton, 2014). However, the cost of an emulsion pump is insignificant when the pump's fixed cost is added to the total explosive costs of the equipment per month.

The performance of explosives in the underground narrow reef is measured through established relationship between the quantity of explosives used (kg) and the production output measured in squared metres (m^2) (Gaula, 2015). The method is widely used to calculate the relationship between explosives usage and production in the gold mines and is called the stope efficiency. The stope efficiency is calculated as the area stoped or tonnages produced per month over the total costs of explosives, accessories, and initiating systems.

2.4.2 Post-blast conditions

Improperly designed blasting activities potentially contributes to underground hazardous conditions through reduction of rock mass competency and damage to the remaining roof, walls or support (Iverson, 2007). The blocky ground formed by the intersection of post blast fractures and the pre-existing geological structures such as joints and faults contributes towards the unsafe conditions (Sellers, 2011).

The unpredictable fall of damaged rock can cause injury to personnel or equipment plus increase in support requirements. Ground control can be improved through blasting practices that are designed for a particular ground condition (Iverson, 2007). Correct application of the selected explosives helps prevent damage to excavations and reduce the exposure of miners to unsafe conditions (Sellers, 2011). The ability to vary explosives density when using pumpable emulsion can help to control the explosives energy in different ground conditions (Pearton, 2014). A good blasting with correct selection of the explosive type, charge mass and round design can improve rock mass conditions and maximise the useful capacity of support units (Sellers et al., 2012). The metric used for the post-blast condition in this research is the hangingwall overbreak, measured by excavation dimension beyond the intended margins.

In turn, the blast damage can be described as the combination of overbreak and the quality of the rock beyond the break limit (Iverson, 2007). Blasting creates a network of fractures which leads to the general deterioration of the rock mass in the blasting area. The fractures are formed by both shock wave and gas penetration in the into the rockmass (AECI Mining Explosives, 2018a).

Overbreak occurs when fractures extend beyond the intended area or line of break (Iverson, 2007). The emulsion explosives are recommended for controlling overbreak in underground due to their higher velocity of detonation when compared to other explosives. The higher velocity of detonation is associated with quick delivery of energy in the initial stage of blasthole expansion when stress waves are generated, leading to limited time available for the penetration of high pressure gases into the surrounding rockmass (COMRO, 1989; Pearton, 2014). The detonation pressure and blasthole diameter are directly related to the energy released by explosives (Iverson, 2007).

2.4.3 Blasting efficiency

Blasting efficiency is an evaluation of the quality of a blast. A quality blast achieves the desired face advance which translates into proportionate ore block of planned production that is extracted from the mine at the required grade (Sebutsoe and Musingwini, 2017). It is worth noting that the required grade in narrow reef mining can be reduced by dilution which occurs as a result of low grade or waste material beyond stope margins mixing with ore within the planned margins, thus reducing the ore value per tonne (Xingwana, 2016).

Furthermore, regular blasting frequency allows the panel to progress ahead of the stressed and deteriorating hangingwall for safety reasons. Achieving full face advance post-blast allows the mine to reach its targeted planned production and reduce the cost of re-drilling, recharging and re-blasting (AECI Mining Explosives, 2018a). It is also important to use the correct quantity of explosives in the process and achieve the correct fragmentation. The former has bearing on the cost of explosives consumed per blast and the latter has bearing on the efficiency of cleaning (ground handling) post blast. In this regard, important KPIs are face advance, powder factor and fragmentation.

Face advance

Mining operation can experience revenue loss through poor advance from the planned stopes influenced by poor blasting practice. The unattained full daily blast advance leads to increase in costs of explosives used to achieve the planned monthly tonnages as additional explosives are used for re-blasting. There are multiple factors that affects advance per blast in narrow reef mining such as drilling control, explosives, rock mass conditions and geological factors, blast design, initiating system, and timing of the round (Pearton, 2014). Successful blasting requires the controllable blast geometry and correct explosives to match the uncontrollable rock conditions (Rajpot, 2009). The effective charge defined as the product of the energy concentration and coupling ratio has influence on the planned burden and blasthole diameter for specific blast outcome (COMRO, 1989).

Powder factor

Singh and Abdul (2012) defined powder factor as the ratio of the total weight of explosives and the amount of rock broken. Later, Torrance and Scott (2015) defined powder factor as the average quantity (mass) of explosives used to blast cubic metre of rock as expressed by Equation 2.1. Generally, the powder factor in practice is derived through experience, rules of thumb or blasting indices. These approaches are retrospective in that the blast outcomes are analysed and the inputs for the next blast is adjusted accordingly to achieve the required results. The outcomes are not modelled or predicted beforehand (Torrance and Scott, 2015).

$$K = \frac{M_t}{L \times A \times W} \qquad Equation\ 2.1$$

Where:

K is powder factor (kg/m^3);

M_t is total mass of explosive (kg);

L is panel Length (m);

A is advance per blast (m); and

W is stope width (m).

Fragmentation

Fragmentation is the main goal of explosives rock breaking. Fragmentation is defined as the size distribution of rock fragments and is dependent on the rock properties, spacing and burden, explosives properties, and explosion gas pressure (Singh and Abdul, 2012; Xingwana, 2016). The suitable fragment size distribution generated by blasting should cater for downstream mine processes (Singh and Abdul, 2012). The desirable muckpile characteristics important for fragmentation were identified to be mean particle size *(Xc*), (that is mean particle size at 50% passing (X_{50})), Index of uniformity (*n*) (that is the ratio of fines to oversized rocks) (Singh and Abdul, 2012).

One of the commonly used technique to measure size distribution is image analysis. In this technique, images of the blasted muckpile are captured by a camera on the face and analysed to assess fragmentation size and distribution. The image analysis applications are based on fragmentation models. A variety of modelling approaches ranging from purely empirical to rigorous numerical models have been used to predict fragmentation. The commonly used and yet simple mean fragmentation predictive tool is the Kuznetsov equation shown in Equation 2.2 (Cunningham, 1983):

$$X_{50} = A.K^{-0.8}Q^{\frac{1}{6}}.\left(\frac{115}{RWS}\right)^{\frac{19}{30}} \qquad Equation\ 2.2$$

Where:

X_{50} is the mean particle size (cm);

A is rock factor,

K is powder factor (kg/m^3)

Q is mass of explosive used (kg); and

RWS is relative weight strength.

The fragmentation distribution vary from mine to mine due to loading, transportation, crushing and milling constraints (Oates and Spiteri, 2021). Large rock fragments can damage stope support and barricades on impact, increase the propensity for secondary blasting or rock-breaking, and/or cause ore pass blockage. Fine fragments can lead to gold ore loss and/or increase the risk of orepass mudrushes. Apart from geological factors, other factors that determine the fragmentation of a specific blast are explosives type, powder factor, drilling and blasting practice, and timing of a blast (Pearton, 2014).

2.5 Use of pumpable emulsion in underground mines

Pumpable emulsion explosives comprise of an ammonium nitrate solution in a continuous oil phase, and is constantly evolving through innovation of various manufactures for application on different mining rock conditions for both surface and underground. Pumpable emulsion explosives in underground hard rock mining are generally used in the development of access tunnels and ring blasting in massive mining. In recent developments, the use of pumpable emulsion explosives has been extended to conventional narrow reef stopes (AEL., 2018). The trials to introduce pumpable emulsion in narrow reef production stopes in South Africa started in late 1980s.

The technical issues identified during the initial trials with respect to pumps were their bulkiness and weight, manoeuvrability in the cramped working spaces and low reliability. There were also challenges associated with the mixing system with regard to ratio of emulsion to gassing sensitiser pumped into blastholes. Other issues were maintenance, stock control and inventory management. The pumps system was improved in later trials to address the technical and ownership issues identified in initial trials (Fourie et al., 2009).

2.5.1 Charging units

The charging units differs in application according to different manufacturers. Broadly, in an underground application there are two types, namely, mobile charging units (MCU) which are used in development ends and charging of rings, and portable charging units (PCU) which are used for charging of narrow reef panels. The development of a PCU has made it possible for the use of pumpable emulsion explosives in underground narrow reef stopes. Figures 2.3 (a) and (b) show pictures of AECI Mining’s MCU and PCU underground, respectively. The units are designed to sensitise the non-explosive emulsion by mixing it with a measured gassing solution to turn the mixture into an explosive while charging a blasthole (AEL., 2018).

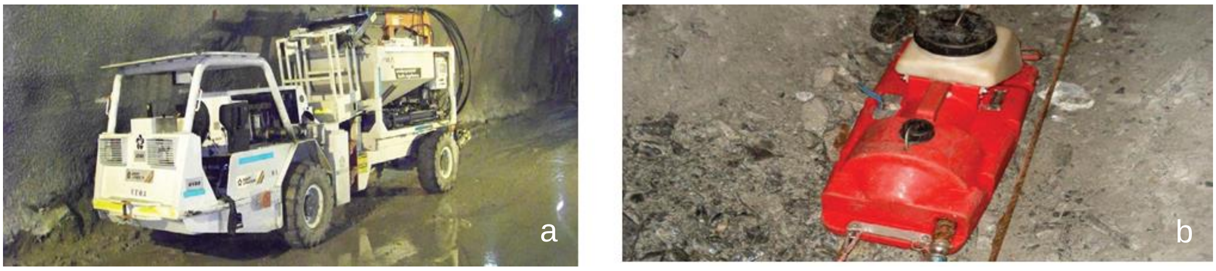

Figure 2.3: (a) Pictures of mobile charging units (MCU) and (b) portable charging units (PCU) underground (AECI Mining Explosives, 2018b)

The charging units are designed to have a fixed ratio of emulsion to sensitiser when charging, which relates to the final density of the product. The AEL Mining's PCU is designed to pump controllable number of charging strokes per blasthole, with each stroke equal of between 200 g and 240 g mass of explosives depending on the PCU setup (AEL., 2018).

2.5.2 Benefits of pumpable emulsion explosives

Comparison studies were done to establish the benefits of pumpable emulsion explosives over other explosive types in underground mining (Bennett and Parsons, 2007). However, the benefits of pumpable emulsion explosives were only quantified in development ends and underground long blastholes (blast rings) and not in conventional narrow reef stopes. Pearson (2015) performed a successful controlled trial to evaluate the viability of emulsion in conventional narrow reef stopes, but the benefits are yet to be studied under normal production environment. The benefits of pumpable emulsion explosives can be generally categorised into operational and financial, and the findings are related to the design perimeters used in the mines as summarised in Table 2.1.

Table 2.1: Operational and financial benefits of pumpable emulsion in an underground operation *(Bennett and Parsons, 2007).*

Description	Operational Benefits	Financial benefits
Water resistance	Wet blastholes can be charged successfully without dewatering. Water is displaced out of the blasthole as emulsion is pumped from the toe.	24% reduction in explosives costs through replacement of packaged emulsions in wet blastholes.
Coupling	100% coupling is achieved with emulsion, which provides much greater energy for breakage.	
Advance rate	100% advance can be achieved after scaling.	An improvement in advance will result in revenue due to the 100% advance achieved per blast
High VoD	The shock energy component is higher in bulk emulsions than ANFO, providing more energy for breaking the rock rather than moving it.	
Face pattern optimisation	Burden increase as the breakage radius for emulsion is greater.	This leads to reduction of blastholes drilled. Less blastholes to drill and charge means saving in time and consumables depending on the pattern.
Charging time	Reduction of time required to charge the stope due to rapid charging process from the pumps; 20%-30% reduction in charging time.	Time saved in charging a face equates to approximately 3% of the overall drill and blast costs for each round.
Metered blasthole loading and explosive consumption	Accurate quantity measurement can be achieved with technology due to the liquid form of the emulsion, reducing over usage.	5.5% reduction in costs through improved metering with longer uncharged collar lengths.

Table 2.1 tabulates the operational and financial benefits of pumpable emulsion explosives in various underground applications. This was key in the comparison of pumpable emulsion explosives to other explosives typically used in underground operations such as ANFO or cartridge explosives.

2.6 Blast optimisation

The main objective of blasting is to achieve productivity and profitability through maximum face advance per length of the blasthole drilled, desired fragmentation and size distribution (Cunningham, 2005; Pearton, 2014)). The combination of the explosives action and the rock reaction determines the blast outcome (Torrance and

Scott, 2015). Explosives and blast design are two variables that can be changed to improve blasting results. However, although the execution of the blast design during marking and drilling is often the issue, explosives are sometimes singled out as the main contributor to poor blasting results (Singh and Abdul, 2012).

Kuz-Ram model is the most common predictive tool used to approximate blasting fragmentation's mean size and uniformity index through a combination of blast design, rock mass and explosives properties (Cunningham, 2005). The relationship between fragmentation and blast design is such that the mean particle size increases with an increase in burden to blasthole diameter ratio, where the change is due to the increase in burden as the blasthole diameter is kept constant. On the other hand, the fragment size decreases with increase in the powder factor (Singh and Abdul, 2012). Other blast design variables that can influence blast outcome include spacing to burden ratio, stemming column length, explosive type and initiation mode (Cunningham, 2005).

2.7 Summary

This chapter covered literature review that aims to contextualise the research and parameters affecting blasting and selection of explosives type. The quality of a blast is generally only scrutinised when the planned production is not achieved or when cost of explosives are high (e.g. greater than the budget) or when poor ground conditions in the panel are experienced. In this respect, quantifying the KPIs would assist the miners to make an informed decision in selecting the right explosive type suitable for their ground condition to achieve the required production, contain explosives costs and ensure safe ore extraction. The methodology in the quantification of the blasting KPIs is discussed in the next chapter.

3 METHODOLOGY

3.1 Introduction

The aim of a research methodology is to guide the researcher in the selection the best approach to address the research questions and objectives. This chapter focuses on the research methodology used to achieve research objectives, which covers research design, data collection process, data analysis approach, data validation process and ethics clearance.

3.2 Research Design

This study was based on a quantitative and qualitative data collection methods. The data collected was categorised into historical and primary data at two shafts where pumpable emulsion explosives were used. Historical data included planned targets and achieved results before and after the introduction of pumpable emulsion explosives, which formed part of quantitative data. The primary data was gathered through underground observations and measurements. The observations constituted both qualitative and quantitative data collection method. The data gathered included among others, ore production, number of panels mined, face advanced, number of blasts per panel per month, mine call factor and explosives consumption. The following methods were used to achieve the research objectives:

- Establish the mine targeted costs and blasting efficiency KPAs;
- Collect historical and primary data as mentioned in Section 3.3;
- Analyse the data with respect to set KPAs;

- Conclude with respect to whether pumpable emulsion explosives are better than cartridge explosives in narrow reef stopes.

3.3 Data collection process

A quantitative and qualitative study was conducted to quantify the benefits of pumpable emulsion explosives at Ya Rona and Hlanganani shafts, both being underground mining narrow reef mining operation. The use of pumpable emulsion explosives at Ya Rona and Hlanganani shafts began towards the end of 2018 and it was fully implemented in March 2019 and December 2020 respectively. The main purpose selecting the two shafts was to gain insight into real-life application of emulsion and noting the experience the crews have in using pumpable emulsion explosives. Anecdotally, the Ya Rona shaft is known to be a low explosives cost operation, while Hlanganani shaft is a high explosives cost operation.

Ya Rona and Hlanganani shafts form part of Driefontein mine complex, which is an intermediate to ultra-deep level gold mine located in the West Rand region on the Western Wits Line of the Witwatersrand Basin, approximately 60 km west of Johannesburg, in the Gauteng Province of South Africa. The Driefontein orebodies comprise of two gold-bearing reefs, namely the Ventersdorp Contact Reef (VCR) which strikes east-northeast with a regional dip of about 21° to the south-southeast, and the Carbon Leader Reef (CLR) which strikes west-southwest and dips to the south at approximately 25°.

Ya Rona shaft mines the VCR, and Hlanganani shaft mines both the VCR and CLR but the stopes considered in this research for Hlanganani shaft mine the CLR. The reefs are laterally continuous and generally less than two metres thick (Sibanye

Stillwater, 2021). The conventional drill-and-blast method is employed at the two operations. The conventional mining method is the most preferred in narrow reef mines because it can navigate complex geological structure, can be applied in smaller stopping heights which help reduce dilution, and is relatively cheaper to implement (Nong, 2010). Figure 3.1 shows the two mines within the Driefontein mine complex.

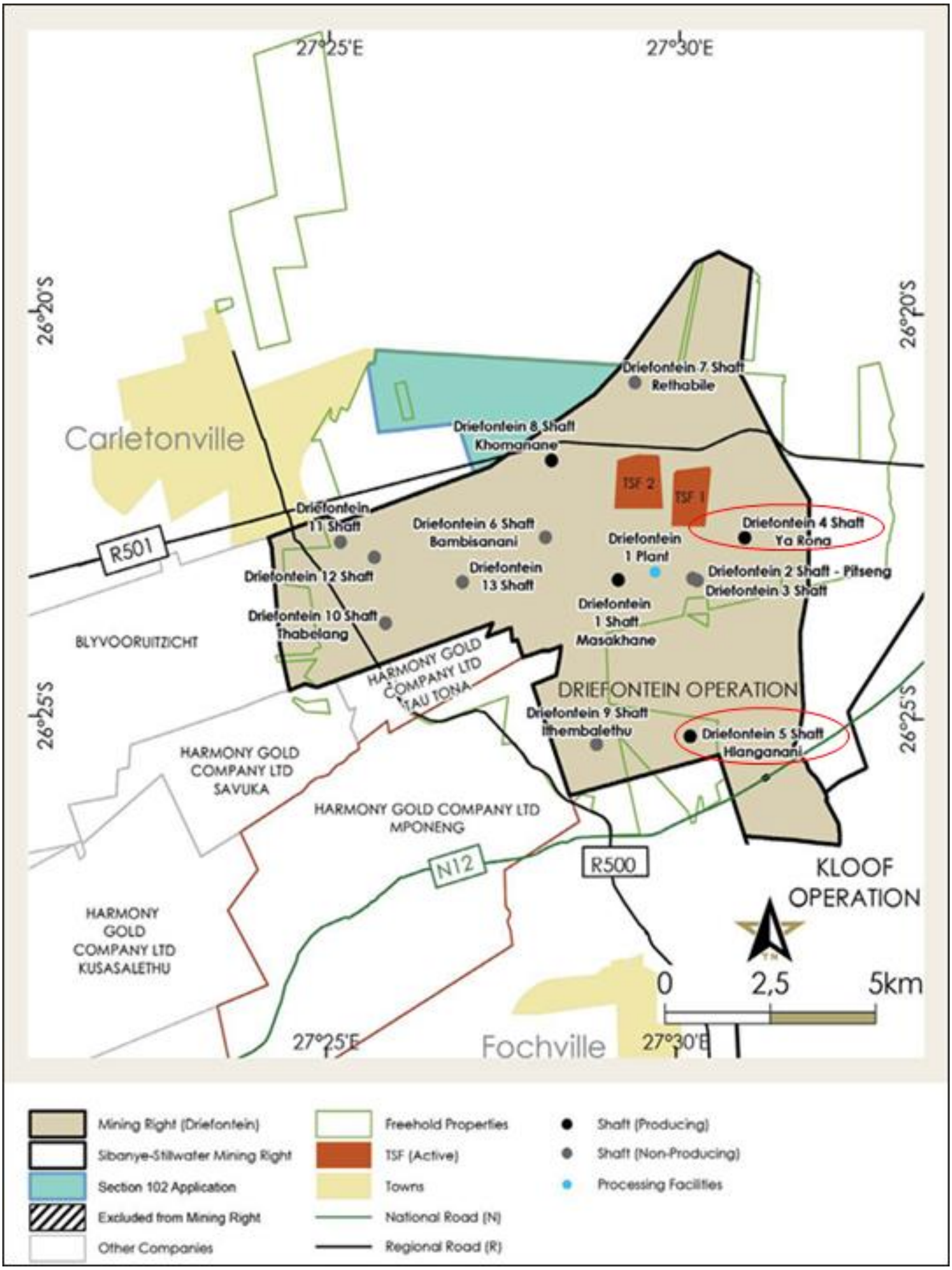

Figure 3.1: Location map of Driefontein mine complex, with Ya Rona and Hlanganani circled in red (Sibanye Stillwater, 2021).

The historical data was sourced from the company's central planning department which is responsible for the production planning and reconciliation post exploitation. The data gathered was from the period when emulsion was first applied in the two shafts. The data includes various results related to mine production at both shafts.

The primary data was collected during underground site visits conducted between August 2022 and January 2023. The data was divided into recorded observations and recorded measurements. Observations were centred on observed drilling and charging practices as well as challenges encountered when using portable charging units. The observations were conducted under normal operation practice and the operators were not coached. Measurements recorded included deviations in marking and drilling, over- or underbreaks, advance rate and fragmentation as well as those related to KPIs mentioned in Section 1.5. Four panels were selected per operation for data collection and each panel was planned to be visited for five consecutive blasts surveys. However, due to operational and safety concerns, permission was granted to conduct the research in only seven panels, four at Ya Rona shaft and three at Hlanganani shaft.

3.4 Data Analysis Approach

The KPIs mentioned in Section 1.5 were compared to either mine targets or industry norms when analysing both historical and primary data. The historical data from the mines will be analysed for blasting efficiency KPIs for the period before and after changes to pumpable emulsion explosives. The recorded primary data was compared to established targets through graphs and other visuals.

As part of the primary data, fragmentation pictures were also taken for one blast per panel and the images were captured near the face before cleaning of the blasted rock can commence. The fragmentation characteristics of the muckpile were analysed using the SPLIT and WIPFRAG photogrammetry. When taking the pictures, the research followed the recommended procedure and guidelines from AECI Mining Explosives when capturing images underground. The procedure highlights the angle of the muckpile, lighting, capturing representative sample and the image scaling. The lighting used was from the camera and the head lamp. Tennis ball or clock card were used as scaling objects.

The number of images required to calculate the size distribution of a given sample of material was not fixed, the selection depended on the quality of pictures in terms visibility and lack of shadows. Similar images were analysed in both SPLIT and WIPFRAG to ensure consistency in terms of data used. The captured image for were uploaded onto each system for analysis. The analysis was done in relation to the image analysis system's manual guidance. The system automatically identifies and quantifies the particles in the image. However, manual editing was done to enhance the delineation by removing false edges and polylines and drawing missing edges. The size distribution of each muckpile was obtained from a combination of multiple images that were analysed.

3.5 Data Validation Process

The selected mines belonging to Sibanye Gold are already fully converted to pumpable emulsion explosives and AECI Mining Explosives supplies them with bagged emulsion as well as technical support. The researched KPIs from the operations were compared with the theoretical calculations, operation targets and industry norms.

3.6 Ethical Issues/Clearance

The necessary permissions to proceed with the research was granted by the two companies involved, that is, AECI Mining Explosives which is the supplier of explosives and Sibanye Gold which owns Hlanganani and Ya Rona shafts. An Ethics Waiver Application form was completed and submitted to the School of Mining Engineering Ethics Committee in line with the objectives of this research and committee took a view that this research posed low ethical risks.

3.7 Summary

This chapter described the methodology used in this research. The methodology formed the bases for gathering and analysing both historic and primary data. The data used in this research was either obtained underground at Hlanganani and Ya Rona shafts or provided by Sibanye Gold. The data and the results thereof are presented in the next chapter in line with the research purpose and objectives.

4 RESULTS

4.1 Introduction

This chapter presents the results collected from the mine which consist of quantitative primary and historical data and underground observations. Presentation of results is in graphics and tables. The actual panel names (numbers) observed in this study are omitted for confidentiality purposes and instead the panels are numbered from 1 to 7.

4.2 Transportation, storage and issuing of pumpable emulsion explosives

The mine is required to establish a logistic system with roles and responsibility about the issuing, transportation and storage of pumps and emulsion explosives on surface and underground. The system was put in place in consultation with the explosives manufacture in adherence to regulations made under Section 30 of the Explosives Act of 1956 on transportation, storage and usage of explosives.

The pumpable emulsion explosives and sensitisers are transported with concealed flatbeds trucks from the AECI Mining Explosives' premises to the mine site. The palletised bags of emulsion are stored on surface within a locked shaded area and are issued in a controlled manner to account for explosives used per miner. The emulsion is transported in one tonne pallet to a central point underground where miners are issued with their ordered quantities and they are also issued with sensitisers in two litres bottles on surface according to their planned blasts.

Each crew is issued with two PCUs, the second PCU is a spare in case of breakdowns. The miner is responsible for keeping the PCU safe, clean and in a good operable state.

If the PCU is damaged by negligence, the miner and the crew can be charged by shaft management.

Each shaft has a system set in place to reduce turnaround time. The shaft has established a workshop on the surface where damaged PCUs can be repaired, and there are workshops underground too for minor repairs. The maintenance personnel are trained by the supplier to maintain and repair units and all breakdowns, repairs, and concerns are required to be recorded miners weekly in logbooks. The logbooks assist with inventory control of spares and highlighting potential areas of improvements.

4.2.1 Emulsion waste and environmental consideration

Emulsion wastage underground occurs during the cleaning of the hose; when disposing of cup samples; as a spillage during the transfer from the bag into the PCU tank; as an overflow from an overcharge blasthole when the gassing process begins; or as outflow from non-tamped blastholes. There is a guideline on treating wastage for different emulsion amounts. The disposal of spillage greater than 2 kg or expired emulsion and sensitisers at the mines must be done following safety operational risk assessment and procedures as contemplated in Regulations 4.1 and 4.2 of the Mine Health and Safety Act Regulations (2018) made under the Mine Health and Safety Act of 1996.

4.3 Planned blast design parameters

The mine's actual production output differ with the planned targets due to the uncertainty associated with technical and human factors. The actual results turn to be lower than the target in most matured mines, due to internal controllable or uncontrollable decision making variables (Sebutsoe and Musingwini, 2017). The two operations of Ya Rona and Hlanganani shafts have converted from using cartridge explosives to emulsion explosives in the stopes.

The two operations use standardised stope blast design with either two or three lines of blastholes. Only one blast design parameter was changed during the conversion from cartridges to emulsion; the blasthole diameter was changed from 34 mm to 32 mm. The blasthole diameter was reduced in consideration of emulsion explosives' 100% coupling which would in effect increase energy delivery (De Beer, 2023). Table 4.1 summarises Sibanye Gold operations' blast design parameters for a panel using emulsion and cartridge explosives.

Table 4.1: Blast design parameters at Ya Rona and Hlanganani shafts

Parameter	Emulsion (UG100+ GS30 sensitiser)	Cartridge (Magnum bustergel 28 x 300 mm)
Drill steel length	1.2 m	1.2 m
Effective blasthole length	0.9 m	0.9 m
Blasthole diameter (d)	32 mm	34 mm
Stemming length	0.32 m	0.34 m
Burden	60 cm	60 cm
Expected blast advance (90% of effective blasthole and above)	0.8 - 0.9 m	0.8 - 0.9 m
Explosives density (ρ)	1 – 1.18 g/cc	1.18 - 1.25 g/cc
Initiating system	Shocktube 200/4000 ms	Shocktube 200/4000 ms
Relative Weight Strength (RWS @100 MPa)	89 MPa	113 MPa
Relative Bulk Strength (RBS @ 100 MPa)	127 MPa	179 – 183 MPa
Velocity of Detonation	4000 – 5500 m/s	2900 – 4000 m/s
Reef type (Ya Rona shaft)	Ventersdorp Contact Reef	Ventersdorp Contact Reef
Reef type (Hlanganani shaft)	Carbon Leader Reef	Carbon Leader Reef
Rock factor (conglomerate/quartzite)	10	10

4.4 Primary results

The primary data was acquired through underground visits at the tow shafts. The recorded observation data was collected using the blast survey audits sheets that were populated with pre-blast activities data such as marking, drilling and charging. The post-blast activities of advance rate and sockets measurement and hangingwall observation were taken during the cleaning of the blasted muckpile on the next day shift. The data obtained from stopes was captured in an Excel spreadsheet for analysis.

A total of seven panels were visited between September 2022 and March 2023, four at Ya Rona and three at Hlanganani. Each panel was visited four or five times. The team's blasting rate controlled the number of days spent with each team to complete the set target of 5 blasts per panel. Table 4.2 shows the summary of blast observations conducted underground at Ya Rona and Hlanganani shafts.

Table 4.2: Summary of blasts observation done at Ya Rona and Hlanganani shafts

Shafts	Number of Panels Visited	Total Number of Blasts Observations	Number of Blasts Observed per Panel
Ya Rona	4	20	5 in Panels 1 to 4
Hlanganani	3	13	5 in Panel 5; 4 in Panels 6 and 7

The panel parameters observed underground were used for calculations in Sections 4.5, 4.6 and 4.7. Table 4.3 and Table 4.4 shows average panel parameters observed at Ya Rona and Hlanganani shafts. See Appendices 1 and 2 for complete calculations.

Table 4.3: Summary of average blast design parameters from observed panels at Ya Rona shaft

	Planned Blast (m²)	Actual Blasted (m²)	Average Planned Equivalent Cartridge Explosives (kg)	Average Planned Emulsion Explosives (kg)	Average Actual Emulsion Explosives (kg)	Actual Stoping Width (cm)	Actual Panel Length (m)
Panel 1	12.78	12.66	51.32	44.64	50.64	209	14.2
Panel 2	16.06	16.06	58.91	51.24	58.76	160	18
Panel 3	15.30	15.11	48.29	42.00	42.00	167	17
Panel 4	22.32	22.22	93.13	81.00	123.40	182	25

Table 4.4: Summary of average blast design parameters from observed panels at Hlanganani shaft

	Planned blast (m²)	Actual blasted (m²)	Average Planned Equivalent Cartridge Explosives (kg)	Average Planned Emulsion Explosives (kg)	Average Actual Emulsion Explosives (kg)	Actual Stoping width (cm)	Actual Panel Length (m)
Panel 6	19.08	18.78	59.46	52.21	51.72	156	21
Panel 7	32.18	31.45	101.75	89.34	88.50	175	35
Panel 8	22.50	22.50	98.13	86.16	92.45	227	25

4.5 Results of blasting efficiency KPA

The blasting efficiency KPA is defined as the propensity to achieve set production factor targets. The KPIs in this respect are face advance (m), powder factor (kg/m^3) and fragmentation distribution (percentage passing). Each KPI was analysed as per data acquired against the established norms.

4.5.1 Face advance

The face advance results achieved at the four observed panels were analysed against the norms. The panels were mined using breast or up-dip method based on the ground available. The full-face advance is the ultimate goal for every blast. The mine's target advance per blast is 90% to 100% of the effective blasthole length drilled. The two operations use a 1.2 m standard drill steel, resulting in an effective blasthole length of 0.9 m, with an acceptable advance per blast range of 0.8 m to 0.9 m.

The face advance per blast was measured using a tape at the top and bottom of the panel after every blast, sockets were also used as a measure of advance per blasthole. Mine Health and Safety Act (1996) defines sockets as "any shot hole, or part of any shot hole, known not to be a misfired hole, which remains after having been charged with explosives and blasted or which, for any other reason, may be suspected of having contained explosives at any time and includes any shot hole, or part of any shot hole, from which all explosives have been extracted". Generally, any blasthole which is longer than 5 cm is regarded as a socket by White et al. (1975).

There are many factors that affect the formation of sockets, but having sockets on the face is a clear sign of a compromised face advance. The cumulative effect of sockets on the advance is apparent after multiple blasts and can affect the panel face shape. The prevalence of sockets on the face post blast can be used as an indicator of a blast success, and the benchmark of sockets prevalence is 10%. The socket prevalence is derived from the quotient of the resultant sockets for the particular blast over the blastholes drilled (see Equation 4.1).

$$Panel\ Socket\ Prevalence = \frac{\sum Socket\ lengths\ in\ panel}{\sum Blasthole\ lengths\ in\ panel} \times 100\% \qquad Equation\ 4.1$$

Face advance at Ya Rona shaft

Figure 4.1 shows the average expected advance per blast against actual advance per blast at the Ya Rona shaft when emulsion explosives were used. As indicated in Table 4.2, there were five blast observations per panel and four panels were observed with Figure 4.2 showing the results of the socket prevalence for each blast.

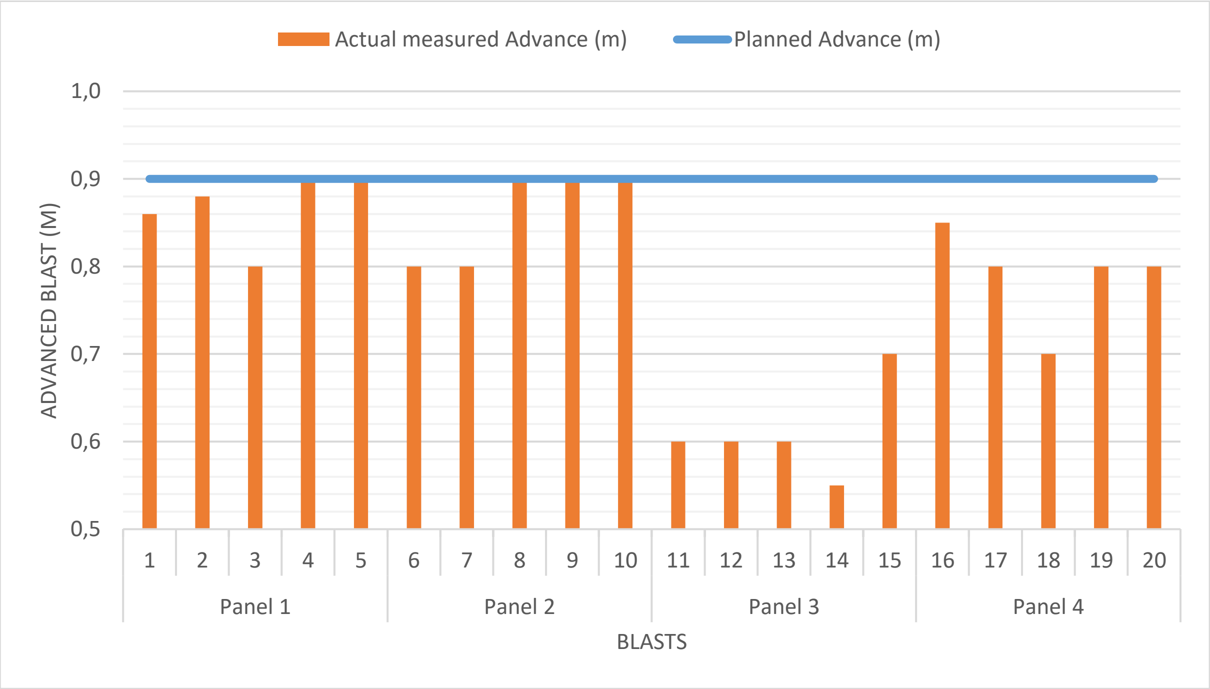

Figure 4.1: The planned advance per blast based on the blasthole length drilled versus average actual advance per blast measured at the Ya Rona shaft when using pumpable emulsion explosives

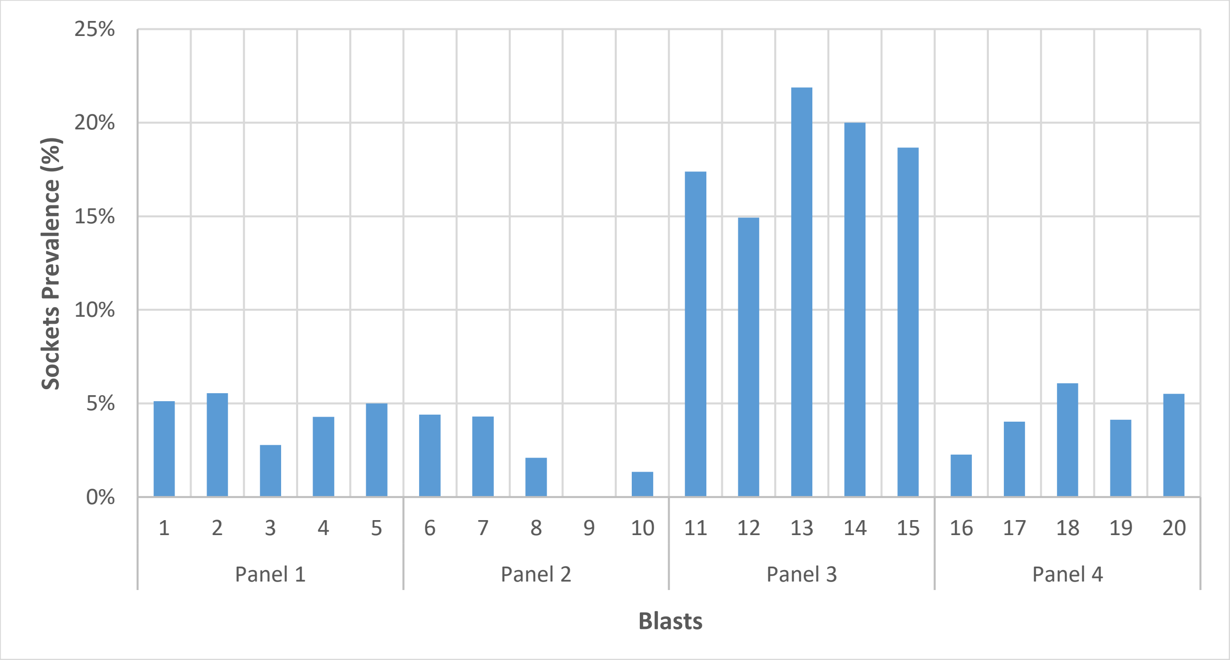

Figure 4.2: The average socket prevalence per blast observed at Ya Rona shaft when using pumpable emulsion explosives

Blast No. 1 to 5 in Figure 4.1 took place in Panel 1 at Ya Rona. Blast No. 1 had an average blasthole length of 0.86 m, which was shorter than the required 0.9 m, but within the range of 0.8 m to 0.9 m. The blasthole length was shorter due to the operators not drilling the required 0.9 m length and Blast No. 3 achieved an advance of 0.8 with no identifiable reasons. Overall all blasts in Panel 1 achieved or exceeded the minimum advance per blast of 0.8 m, which is acceptable. The socket prevalence in Panel 1, as shown in Figure 4.2, was below the 10% threshold.

Blast No. 6 to 10 in Figure 4.1 took place in Panel 2. The average achieved advance per blast was 0.8 m for Blasts No. 6 and 7and 0.9 m for Blasts No. 8 to 9, which overall was acceptable. The socket prevalence in Panel 2, as shown in Figure 4.2, was less than 2% on average which can be classified as extremely good.

Blast No. 11 to 15 in Figure 4.1 took place in Panel 3. The results in Panel 3 were characterised by poor advance per blast and high prevalence of sockets. Panel 3 was mining up-dip with an apparent dip of 22°, indicating a possibility of emulsion slumping from the toe towards the collar. The face advance for Blast No. 11 to 13 was 0.6 m, that of Blast No. 14 was 0.55 and Blast No. 15 was 0.7 m. The average socket prevalence in Panel 3, as shown in Figure 4.2, was approximately 19%, with the highest peaking at 22% (Blast No. 13), with some blastholes having sockets as long as of 0.5 m. The high prevalence of sockets for Blast No. 13 was amplified by fewer blastholes compared to Blast No. 14 despite having the same panel width and length.

Blast No. 16 to 20 in Figure 4.1 took place in Panel 4. The average advance per blast for all five blasts was approximately 0.8 m. Blast No. 18 had advance per blast of 0.7 m due to poor emulsion gassing as the pump was not functioning optimally. The average socket prevalence in Figure 4.2 was less than 10%, with the highest socket prevalence being 7% in Blast No. 18 due to some blastholes having sockets as long as 0.2 m.

Face advance at Hlanganani shaft

Figure 4.3 shows the planned advance per blast against actual advance per blast at the Hlanganani shaft when emulsion explosives were used. As indicated in Table 4.2, five blasts were observed in Panel 5 and four blasts each were observed in Panels 6 and 7, and Figure 4.4 shows the results of the socket prevalence for each blast.

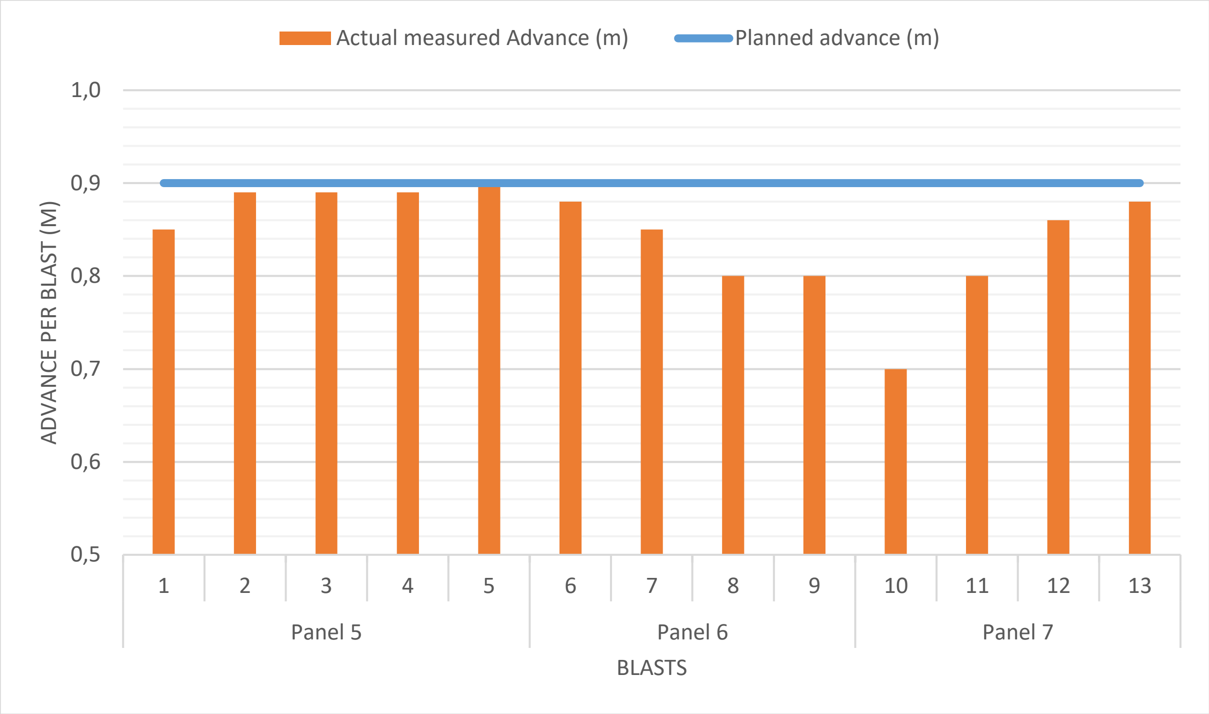

Figure 4.3: The planned advance per blast based on the blasthole length drilled versus average actual advance per blast measured at the Hlanganani shaft when using pumpable emulsion explosives

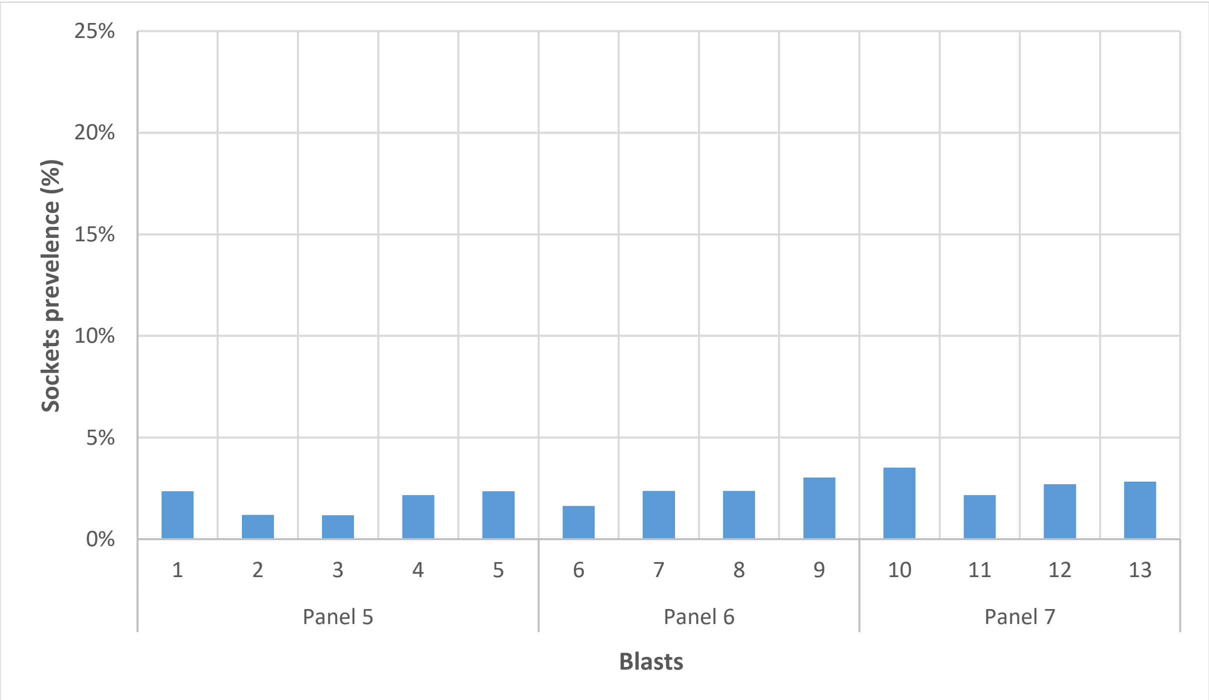

Figure 4.4: The average sockets prevalence per blast observed at Hlanganani shaft when using pumpable emulsion explosives

Blast No. 1 to 5 in Figure 4.3 took place in Panel 5 at Hlanganani shaft. The planned blasthole length was 0.9 m and the average effective length was between 0.86 m and 0.89 m for Blast No. 1 to 4 and Blast No. 5 was fully drilled. The socket prevalence in Panel 5, as shown in Figure 4.4, was below 5%.

Blast No. 6 to 9 in Figure 4.3 took place in Panel 6 at Hlanganani shaft. Blast No. 6 had an average advance of 0.88 m and Blast No. 7 had an average advance of 0.85 m, whereas Blasts No. 8 and 9 had average advance of 0.8 m each. The advance per blast of less than 0.9 m can largely be attributed to poor drilling practice. The average socket prevalence for all the blasts in Panel 6 was approximately 2% as shown in Figure 4.4, indicating an overall acceptable blast results.

Blast No. 10 to 13 in Figure 4.3 took place in Panel 7 at Hlanganani shaft. All the blasts had an average actual length less than 0.9 m. Blast No. 10 had a face advance of 0.7 m, the only one below 0.8 m. The drilling angle in the middle holes in Blast 10 were between 70° to 80° to the horizontal plane. The socket prevalence for Blast No. 10 was also high at 4% but still below the benchmark of 10%. Overall, the blast advance was better but still a concern for Blasts No. 11, 12 and 13.

4.5.2 Powder factor

The actual powder factor for each blast was calculated using Equation 2.1. The equivalent planned powder factor of cartridge explosives was calculated using the blast design parameters and the equivalent planned mass of explosives of cartridges per blasthole was estimated to be 0.69 kg compared to the planned mass of 0.6 kg per blasthole for emulsion explosives. It should be noted that the equivalent powder factor for cartridge explosives was based on a scenario where cartridges would be used instead of pumpable emulsion explosives. The actual powder factor for emulsion explosives was calculated using the actual mass of explosives pumped per blast and the actual volume of rock blasted. The actual mass of emulsion explosive per blasthole varied between 0.6 kg and 1 kg per hole. Appendices 3 and 4 show the calculated results of actual explosives mass, powder factor, and the resultant fragmentation at Ya Rona and Hlanganani respectively.

In this research, the adjusted planned powder factor for emulsion explosives was used. While the planned powder factor for emulsion explosives was based on the charge plan, the adjusted planned powder factor for emulsion explosives catered for the actual site conditions encountered underground such as variation in actual face length or stope width compared to the plan. These variations may be due to poor ground conditions, change in geology or poor mining practice. Ya Rona and Hlanganani's drilling guideline states that three rows of blastholes must be drilled where the planned panel width exceeds 150 cm and two rows equal or below this width. This guideline has material effect on the powder factor. There were instances where the panel width varied above and below 150 cm along the panel face.

Powder factor at Ya Rona shaft

Blast No. 1 to 5 in Figure 4.5 shows results for Panel 1 at Ya Rona. The actual powder factor for Blasts No. 4 and 5 were significantly higher than the adjusted planned powder factor of emulsion and equivalent planned cartridge explosives powder factor because blastholes were charged with an extra 0.2 kg of explosives on average, which resulted in a spike in the actual powder factor. It was also observed that, in general, the actual stope width in Panel 1 was less than the planned stope width, resulting in a higher overall actual powder factor.

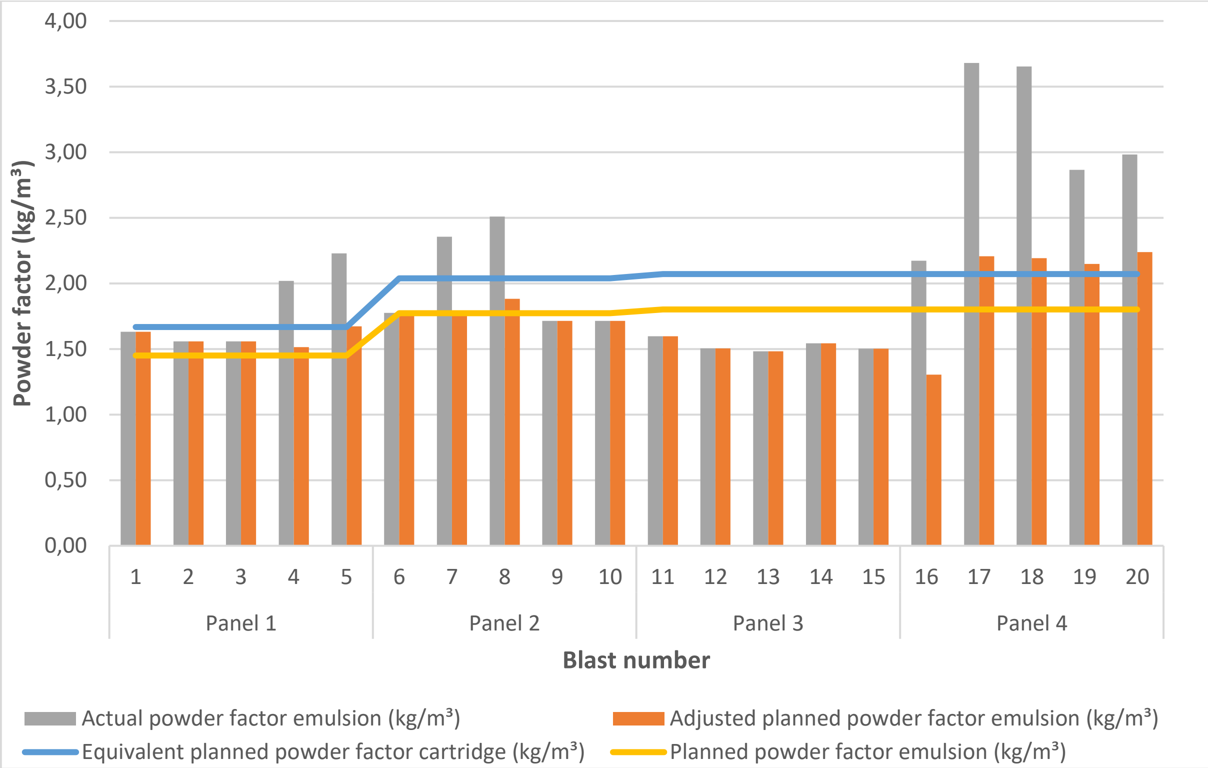

Figure 4.5: Ya Rona shaft plots of calculated powder factors for planned cartridge and emulsion explosives and the actual powder factor for emulsion explosives.

Blast No. 6 to 10 in Figure 4.5 shows results for Panel 2 at Ya Rona. Blast No. 7 and 8 had a higher powder factor due to excessive emulsion explosives pumped per blasthole, where an additional 0.2 kg was added to the planned mass of explosives per hole of 0.6 kg. On the other hand, the actual powder factors of Blasts No. 6, 9 and 10 were the same as the adjusted planned powder factor.

Blast No. 11 to 15 in Figure 4.5 shows results for Panel 3 at Ya Rona. The actual emulsion powder factor achieved was the same as the adjusted planned powder factor but lower than the planned emulsion powder factor. The reason for lower than the planned emulsion powder factor was due to two rows of blastholes being drilled instead of three rows; therefore, less overall mass of explosives was charged per blast. The reason for non-adherence to the mine's drilling guideline was poor mining practice resulting from the challenges of up-dip mining.

Blast No. 16 to 20 in Figure 4.5 shows results for Panel 4 at Ya Rona. All blasts in Panel 4 had higher actual powder factor than the adjusted planned and planned powder factors. The mass of explosives per hole was between four and five strokes instead of the planned three strokes; each stroke is 0.2 kg, which meant the blastholes were overcharged. The excessive actual powder factor might have contributed to the observed hangingwall overbreak as outlined in Section 4.5.1 of this report. Blast No. 16 consisted of two rows of blastholes and this was corrected to three rows for Blasts No. 17 to 20. The mine's drilling guideline of drilling three rows in areas where stoping width is above 1.5 m was not adhered to in Blast No. 16.

Powder factor at Hlanganani shaft

Blast No. 1 to 5 in Figure 4.6 shows the results for Panel 5 at Hlanganani. The actual powder factor for all Panel 5 blasts were equal to the adjusted planned emulsion powder factor but lower than planned power factor for emulsion and cartridge explosives.

Blast No. 6 to 9 in Figure 4.6 shows the results for Panel 6 at Hlanganani. The powder factor plot shows similar trend to that of Panel 5 with the actual emulsion powder factor being equal to the adjusted emulsion powder factor but still lower than the planned emulsion and cartridge explosives. The increase in powder factor in Blast No. 9 is due to an increase in the number of holes charged in the panel. The crew drilled three rows as per mine's guideline instead of two rows drilled in Blasts No. 6 to 8. The increased number of holes significantly increased the total mass of explosives charged.

Blasts 10 to 13 in Figure 4.6 shows the results for Panel 3 at Hlanganani. Blast No. 10 shows a higher powder factor for the actual emulsion explosives than the planned and adjusted planned emulsion powder factors. The higher powder was due to overcharging blastholes by 0.2 kg of emulsion explosives in each blasthole, instead of the required 0.6 kg. The actual and adjusted planned emulsion powder factors in Blasts No. 11 to 13 were higher than the planned emulsion powder factor due to an increase in number of holes drilled and charged as the results of increased stoping width. An increase in the number of holes drilled in Blast No. 11 to 13 increased the mass of explosives for actual and adjusted powder factors.

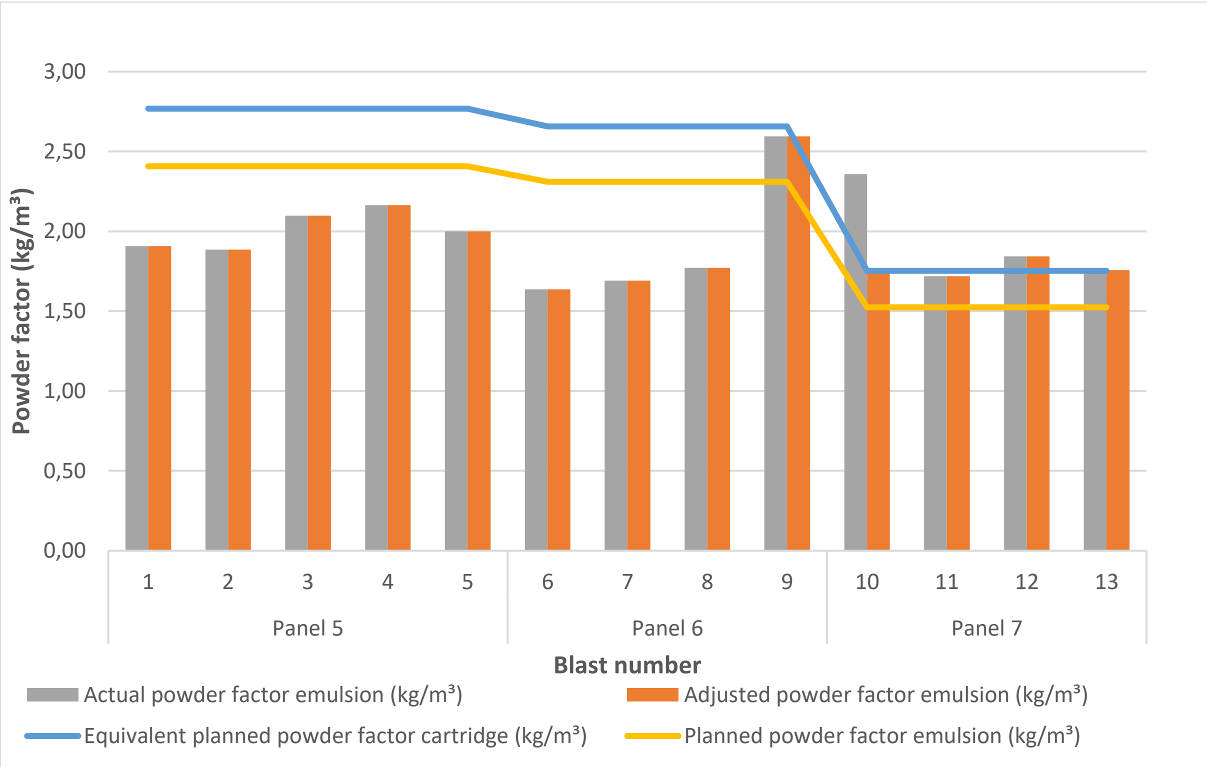

Figure 4.6: Hlanganani shaft plots of calculated powder factors for planned cartridge and emulsion explosives and the actual powder factor for emulsion explosives.

4.5.3 Fragmentation

Both shafts consider the mean blasted particle size (X_{50}) of between of 11.5 cm and 13.5 cm as a key indicator of a successful blast. The SPLIT and WIPFRAG image analysis systems were used to assess fragmentation characteristics of the muckpile while the Kuz-Ram equation (Equation 2.2) was used to calculate the expected X_{50} of the muckpiles for both emulsion and cartridge explosives. The image analyses and

Kuz-Ram calculations were compared to expected range to determine whether the fragmentation was acceptable. Figure 4.7 (a) and (b) shows an example of muckpile images used for analysis in both SPLIT and WIPFRAG, with a tennis ball used as a scaling object.

The rock factor of 10 used in Kuz-Ram calculations (Equation 2.2) was derived from the known uniaxial compressive strength of VCR mined at Ya Rona and CLR mined at Hlanganani (AECI Mining Explosives, 2018a). The expected X_{50} of emulsion explosives and equivalent X_{50} of cartridge explosives were based on planned mass of explosives and panel volume. Both equivalent cartridge X_{50} and expected X_{50} emulsion were predicted using the Kuz-Ram equation. Equivalent X_{50} cartridge 's calculation was only indicative as both shaft had already converted to pumpable emulsion explosives.

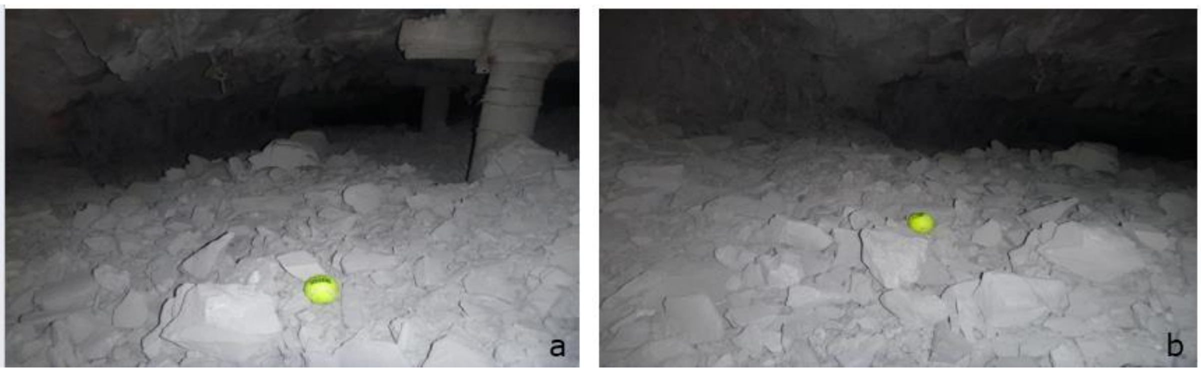

Figure 4.7: An example of muckpile pictures used for fragmentation analyisis in both WIPFRAG and SPLIT image analysis systems.

Ya Rona fragmentation

Table 4.5 shows Ya Rona's calculated expected and equivalent X_{50} of emulsion and cartridge explosives respectively, and that of SPLIT and WIPFRAG image systems analyses. Only a muckpile of one blast per panel was photographed to limit the disruption to production.

Table 4.5: The average Ya Rona expected X_{50} of pumpable emulsion and equivalent X_{50} of cartridge explosives based on the mine charge designs, and the X_{50} results of SPLIT and WIPFRAG image analyses

	Equivalent Cartridge X_{50} (cm)	Expected Emulsion X_{50} (cm)	Emulsion X_{50} from Analysed Images (cm) SPLIT	Emulsion X_{50} from Analysed Images (cm) WIPFRAG	Ya Rona's Target X_{50} Range (cm)
Panel 1 Blast 3	5.96	7.57	7.48	14.1	11.5 - 13.5
Panel 2 Blast 7	5.39	6.85	5.73	13.63	11.5 - 13.5
Panel 3 Blast 15	6.14	7.80	3.58	12.84	11.5 - 13.5
Panel 4 Blast 18	4.54	5.76	5.94	12.81	11.5 - 13.5

The SPLIT image analyses of Blasts No. 7, 15 and 18 showed a finer fragmentation than the expected emulsion explosives X_{50} with Blast 3 showing slightly higher X_{50}. However, the X_{50} of SPLIT image analyses of Blasts No. 3, 7 and 18 were coarser than the equivalent cartridge explosives X_{50}, with Blast No. 15 showing significantly finer fragmentation. It is not clear why the fragmentation in Blast No 15 was finer given that it was one of the blasts with a low powder factor. Overall, the X_{50} of SPLIT's analysed images and the expected emulsion and equivalent cartridge explosives X_{50} were below the target range of 11.5 cm to 13.5 cm.

The WIPFRAG X_{50} of Blasts No. 7, 15 and 18 were within the shaft's target range whereas that of Blast No. 3 was above this range. The huge difference between the Kuz-Ram predictions and the WIPFRAG analyses be attributed Kuz-Ram's poor prediction in the fines range (Lawal, 2021).

Hlanganani fragmentation

Table 4.6 shows Hlanganani's expected and equivalent X_{50} of emulsion and cartridge explosives respectively, as well as and the X_{50} of SPLIT and WIPFRAG image systems analyses. Again, only a muckpile of one blast per panel was photographed to limit the disruption to production.

Table 4.6: The average Hlanganani expected X_{50} of pumpable emulsion and equivalent X_{50} of cartridge explosives based on the mine charge designs, and the X_{50} results of SPLIT and WIPFRAG image analyses

	Equivalent *Cartridge X_{50} (cm)*	Expected *Emulsion X_{50}* (cm)	Emulsion X_{50} from Analysed Images (cm) SPLIT	Emulsion X_{50} from Analysed Images (cm) WIPFRAG	Hlanganani's Target X_{50} Range (cm)
Panel 1 Blast 3	4.7	5.96	5.08	11.69	11.5 - 13.5
Panel 2 Blast 1	5.73	7.28	8.49	11.31	11.5 - 13.5
Panel 3 Blast 13	5.41	6.87	8.63	9.73	11.5 - 13.5

The X_{50} muckpile images of Blast No. 6 and 13 analysed through SPLIT were coarser than the calculated X_{50} of emulsion and cartridge explosives. The SPLIT X_{50} of Blast No. 3 finer than that of the emulsion explosives but coarser than that of equivalent cartridge explosives. However, all three X_{50} were finer or less than the shaft's target range of 11.5 cm to 13.5 cm. The WIPFRAG system depicted a much coarser fragmentation above the X_{50} of both emulsion and cartridges explosives, with Blasts No. 3 and 6 falling within the shafts's target range of 11.5 cm to 13.5 cm and Blast No. 13 falling below this range.

The difference of KUZ-Ram predictions of X_{50} of cartridge and emulsion was relatively small, with use of emulsion predicting coarser fragmentation. However, the difference between the X_{50} SPLIT and WIPFRAG for all blasts was relatively large, with SPLIT showing finer fragmentation than WIPFRAG. The reason for the difference could be due to the inherit difference in the two system's capabilities as elaborated on in section 5.4 of this research. The difference in percentage between the two programmes' analyses ranges from 47% to 72% for Ya Rona and from 11% to 57% for Hlanganani.

4.6 Results of post blast conditions KPA

The rock mass structure, blast geometry and the amount of explosive used influence the extent of the damage in the remaining in-situ rock mass. The breaking of the rock by blasting beyond the intended panel margins is called overbreak (Iverson, 2007). The overbreak can be in the footwall or hangingwall, and it leads to dilution of ore and can cause safety hazards if it is in the hangingwall, particularly in narrow reef mining (Xingwana, 2016).

4.6.1 Hangingwall overbreak

The expected hangingwall overbreak of both Ya Rona and Hlanganani shafts is 0 cm above the top reef contact. The differences between planned and actual stope widths were used to calculate the overbreak. The actual stope width was measured 2 m to 3 m away from the face, and multiple measurements were taken from the hangingwall to the footwall at 3 m to 5 m intervals along the panel length.

Hangingwall overbreak at Ya Rona

Blasting distributes explosives energy into the rock mass. The top row is planned to be drilled 30 cm from the top reef contact to control the hangingwall overbreak. The planned burden between the holes is 60 cm, and the drilling direction should be 90° to the face vertical plane. Table 4.7 shows the summary measurements taken at Ya Rona.

Table 4.7: Summary of the measurement taken at Ya Rona shaft post blasting

Panel	Number of Blasts	Planned Stope Width (cm)	Average Actual Stope Width (cm)	Average Overbreak (cm)
1	5	220	210	-10
2	5	180	180	0
3	5	180	175	-5
4	5	180	192	12

In Panel 1, the average stope width was below the planned stope width for all measurements taken, leading to an average underbreak of 10 cm below the planned stope width. The stope width increased on the footwall side over several blasts from 187 cm in Blast No. 1 to 217 cm in Blast No. 5. The measured burden between the blastholes for all the blasts in Panel 1 was between 55 cm and 70 cm, and the drilling direction was between 70° and 90° to the horizontal.

In Panel 2, the average actual stope width was 180 cm, without any overbreak measured. The measured burden between the blastholes for all the blasts in Panel 2 was between 58 cm and 62 cm and the drilling direction was between 80° and 90° to the horizontal.

In Panel 3, the average actual stope width was less than the planned stope width with an average of 5 cm underbreak. The measured burdens between the blastholes for all the blasts in Panel 3 was between 53 cm and 63 cm, and the drilling direction was between 80° and 90°to the horizontal.

Panel 4 intersected two faults which displaced the reef in Blasts No. 19 and 20, with part of the panel being off-reef. The lava in the hangingwall, which is known to be highly susceptible to overbreaking after a blast, was exposed. The overbreak in Blasts No.

19 and 20 increased by 23 cm to 30 cm along the panel in the hangingwall. The measured burden between the holes for all the blasts in Panel 4 ranged from 59 cm to 64 cm, and the drilling direction was between 80° and 90° to the horizontal.

Hangingwall overbreak at Hlanganani

The hangingwall overbreak measurements were also taken at Hlanganani shaft. Table 4.8 shows the summary measurements.

Table 4.8: Summary of the measurement taken at Hlanganani shaft post blasting

Panel	Number of Blasts	Planned Stope Width (cm)	Average Actual Stope Width (cm)	Average Overbreak (cm)
5	5	135	156	21
6	4	142	175	33
7	4	214	227	13

In Panel 5, the average stope width was above the planned stope width for all observed blasts, leading to an average overbreak of 21 cm. The measured burden between the blastholes for all the blasts in Panel 5 was between 60 cm and 80 cm, and the drilling direction was between 88° and 90°. The average of 80 cm burden was measured on the bottom row of Blast No. 4.

In Panel 6, the average stope width was 33 cm above the planned stope width. The measured burden between the holes for all the blasts in Panel 6 was 55 cm on average in Blast No. 6 to 8 and 60 cm in Blast No. 9. The drilling direction was close to 90° to the horizontal.

In Panel 7, the average measured stope width was 227 cm against the planned stope width of 214 cm, with an average hangingwall overbreak of 13 cm. The mining face had internal waste (quartzite) and multiple bands of carbon leader reefs were mined, contributing to an overall increase in the stope width of over 2 m. Three rows of blastholes were drilled in the panel to cater for increased stope width as per the shaft standard. The measured burden between the holes for all the blasts in Panel 7 was between 57 cm and 65 cm, and the drilling direction ranged from 86° to 90° to the horizontal.

4.7 Results of explosive costs KPA

The total cost of explosives in a panel includes initiating system and accessories, tamping material, and explosives. In the case of pumpable emulsion explosives, the purchase cost of the PCU and its maintenance add another component to costs. In this research, the cost of initiating system, accessories, and tamping material were not analysed because they are common to all types of explosives used to blast panels.

The cost of PCU maintenance pumps covers labour and spares, excluding the purchase cost of PCU. The equivalent purchase cost of the PCU per month is insignificant when added to the total explosives costs in a month (Pearton, 2014). The labour required depends on the number of pumps per operation, and monthly spares expenditure depends on the breakdowns or mechanical failures.

4.7.1 The pumpable emulsion explosives cost breakdown

The cost of emulsion explosives is calculated from the average annual emulsion explosives cost per kilogram. The maintenance labour cost (MLC) for every mass of explosives pumped can be determined from Equation 4.2, and the average spares cost (SC) per mass of explosives is calculated using Equation 4.3.

$$MLC = \left(\frac{l_c}{b_n \times e_m \times PCU_n}\right) \qquad Equation\ 4.2$$

$$SC = \left(\frac{s_c \times PCU'_n}{b_n \times e_m \times PCU_n}\right) \qquad Equation\ 4.3$$

Where:

MLC is maintenance labour cost per kg of emulsion explosives;

SC is spares cost per kg of emulsion explosives;

l_c is cost of labour per shaft;

b_n is number of blasts

e_m is pumpable emulsion explosive mass per blast;

PCU_n is the number of PCU per shaft;

S_c is the cost of spares; and

PCU'_n is the number of PCU in use per panel.

Prices used in this research do not reflect service level agreements between the supplier and the mine (shafts). Each crew was allocated two PCUs at both Ya Rona and Hlanganani shafts, and the shafts had 46 and 90 PCUs respectively, with two people per shaft employed for maintenance. Based on the 2022 costs, the average maintenance labour cost per month was R40 000 for both Ya Rona and Hlanganani, and the average cost of spares ordered per month was R43 000 and R65 000 respectively.

The cost of emulsion explosives in 2022 was R16 316.12 per tonne and the cost of the cartridge explosives was R677.60 per case of 25 kg. The average rate of blasts per panel per month was 7, and the average mass of explosives pumped per blast was 75 kg at both shafts. The total emulsion explosives cost is a combination of maintenance cost, emulsion explosives cost, and spares cost, and the cost breakdown for emulsion explosives and cartridge explosives is shown in Table 4.9.

Table 4.9: Cost comparison of emulsion explosives versus cartridge explosives at both Ya Rona and Hlanganani shafts

Item	Ya Rona costs	Hlanganani costs
Emulsion explosives costs (R/kg)	16.32	16.32
Maintenance labour cost (R/kg)	3.31	1.69
Spares costs (R/kg)	3.56	2.75
Total emulsion explosives (R/kg)	23.19	20.76
Cartridge explosives cost (R/kg)	27.10	27.10

4.7.2 Explosive costs

The cost of explosives is an important measure used to evaluate the wastage or economic use of the explosives. This is done by comparing the planned centares and actual booked/measured centares. The number of charged blastholes planned to blast certain centares are used to calculate the total mass of explosives required in that particular blast. The planned mass of explosives per centares is compared to the actual mass explosives used.

Explosive costs at Ya Rona

The costs of explosive per centares for Blasts No. 1 to 20 at Ya Rona are shown in Figure 4.8. It should be noted that the cartridge explosives indicate the equivalent explosive cost per centare for comparison purposes.

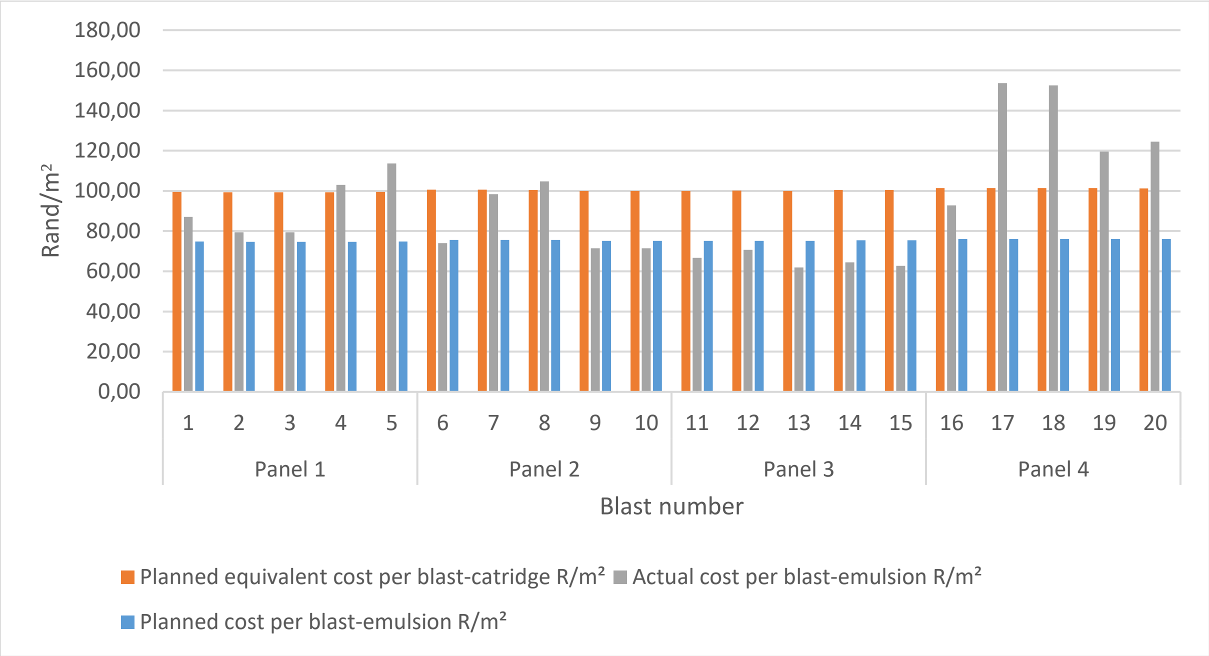

Figure 4.8: The cost per blast comparison of planned and actual usage of explosives for Panels 1 to 4 at Ya Rona shaft

Blasts No. 1 to 5 in Figure 4.8 show the explosives cost results for Panel 1 at Ya Rona. The cost of actual emulsion explosives used for Blasts No. 4 and 5 was significantly higher than that of planned emulsion explosives, whereas the actual cost of emulsion explosives in Blasts No. 1 to 3 were comparatively less but still higher than planned due to a higher number of blastholes drilled compared to planned, resulting in an increase in total mass of emulsion charged.

Blasts No. 6 to 10 in Figure 4.8 shows explosive costs for Panel 2 at Ya Rona. The actual emulsion explosives cost in Blast No. 6 was as per plan whereas the actual costs of Blasts No. 7 and 8 were higher due to an additional 0.2 kg of emulsion explosives per blasthole being added to the planned 0.6 kg per blasthole. This resulted in an increase in the overall mass of explosives per blast, which led to an increase in the cost of actual emulsion explosives. The actual emulsion explosives cost per centare in Blasts No. 9 and 10 were less than planned due to the actual number of drilled blastholes being less than the planned number of blastholes which resulted in less mass of explosives than planned to be charged. The difference in number of blastholes can be attributed to lack of adherence to the plan.

Blast No. 11 to 15 in Figure 4.8 shows explosive costs for Panel 3 at Ya Rona. The actual cost of the five blasts in Panel 3 were less than planned due to two rows of blastholes being drilled instead of three rows; therefore, less overall mass of explosives was charged per blast due to difficulty in drilling up dip.

Blast No. 16 to 20 in Figure 4.8 shows explosive costs for Panel 4 at Ya Rona. The cost of actual emulsion explosives was higher than the planned emulsion explosives, and this was due to overcharging observed for all the blasts, where four or five strokes were charged instead of the planned three strokes for each blasthole. The blastholes in Blasts No. 17 and 18 were charged with 1 kg of emulsion, resulting in the actual emulsion cost being 107% higher than the plan.

Explosive costs at Hlanganani

The cost of explosive per centares for Blasts No. 1 to 13 at Hlanganani are shown in Figure 4.9. As in Figure 4.8, the cartridge explosives in Figure 4.9 indicate the equivalent explosive cost per centare for comparison purposes.

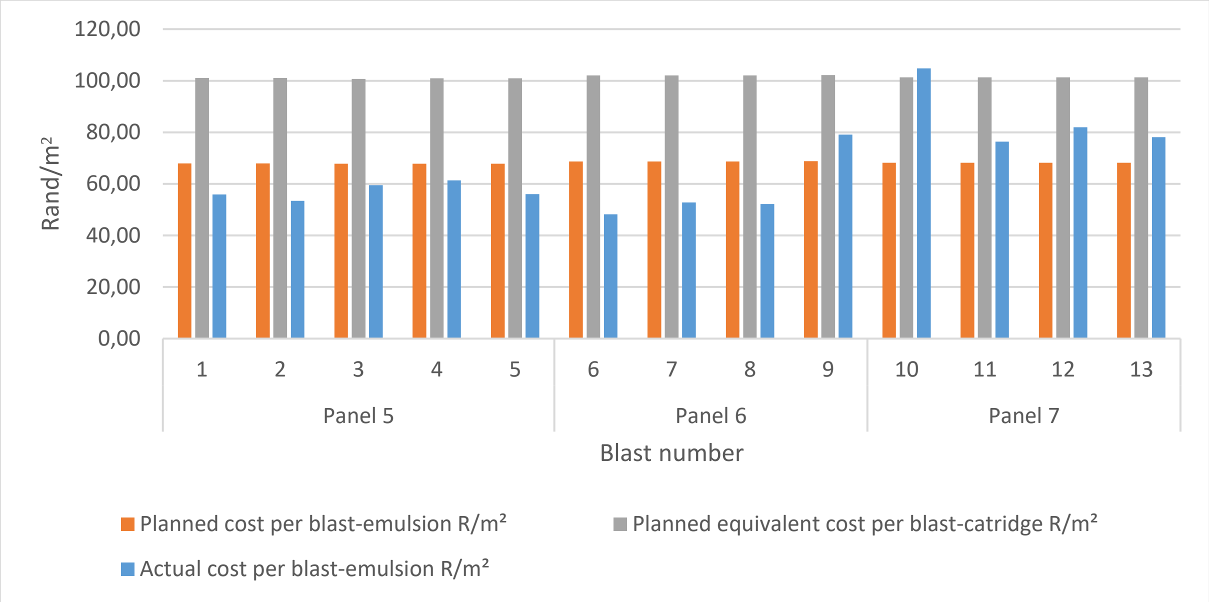

Figure 4.9: The cost per blast comparison of planned and actual usage of explosives for Panels 5 to 7 at Hlanganani shaft

Blasts 1 to 5 in Figure 4.9 shows explosive costs for Panel 5 at Hlanganani. The actual cost per centare for emulsion explosives in Blasts No. 1 to 5 was less than planned. The cost actual of Blasts No.1 to 5 was lower than planned due to fewer blastholes drilled compared to the plan, which resulted in the reduction in the total mass of emulsion explosives charged. The reason for fewer number of blastholes drilled was due to two rows of blastholes being drilled instead of three rows; therefore, less overall mass of explosives was charged per blast. The reason for two rows being drilled was non-adherence to the mine's drilling guideline.

Blast No. 6 to 9 in Figure 4.9 shows explosive costs for Panel 6 at Hlanganani. The actual costs of emulsion explosives per centare for Blasts No. 6 to 8 were less than planned, again this was due to fewer blastholes drilled because of two rows of blastholes drilled instead of the required three rows; thereby, reducing the total mass of explosives charged. The high blasting cost per centare in Blast No. 9 was due to the crew drilling three rows as planned, but exceeding the number of planned blasthole, resulting in higher mass of explosives charged than planned. The excess number of blastholes drilled can be attributed to poor supervision.

Blasts No. 10 to 13 in Figure 4.9 shows explosive costs for Panel 7 at Hlanganani. Blast No. 10 shows significantly higher actual cost per centare compared to the plan due to an additional 0.2 kg mass of explosives per blastholes and the higher number of drilled blastholes resulting in the overall increase in the mass of explosives. The reason for excess number of blastholes drilled can be attributed to a larger stope width that led to arbitrary drilling of additional holes as the crew attempted to reduce the burden. This also applied to Blasts No. 11 to 13.

4.8 Comparison of emulsion and cartridge explosives performance

In this research, the explosive performance was determined by calculating the face advance achievement percentage (FAA%) for emulsion and cartridge explosives. The FAA% was calculated using Equation 4.4, with the FAA% target range being between 90% and 100%. The data for FAA% was obtained from the shafts.

$$FAA\% = 1 - \frac{(n \times l) - f}{n \times l} \times 100\% \qquad Equation\ 4.4$$

Where:

FAA% is face advance achievement percentage;

n is the number of blast per month per panel;

l is standard effective blasthole length; and

f is the actual face advance per month per panel

The face advance data discussed in Sections 4.8.1 and 4.8.2 are the average monthly advance for all production crews at each shaft. The number of crews varied per month in all the years analysed, ranging from 14 to 29 at Ya Rona and 14 to 48 at Hlanganani.

4.8.1 Ya Rona FAA%

The 2017, 2020 and 2021 periods were compared for Ya Rona shaft. In 2017 only cartridge explosives were used, and in 2020 and 2021 the shaft was fully converted to emulsion explosives. The 2018 and 2019 data were omitted as this was considered as a transition period. Figure 4.10 compares 2017 face advance with 2020 and 2021 face advance at Ya Rona shaft, while Figure 4.11 compares the 2017, 2020 and 2021 average face advance achievement percentage.

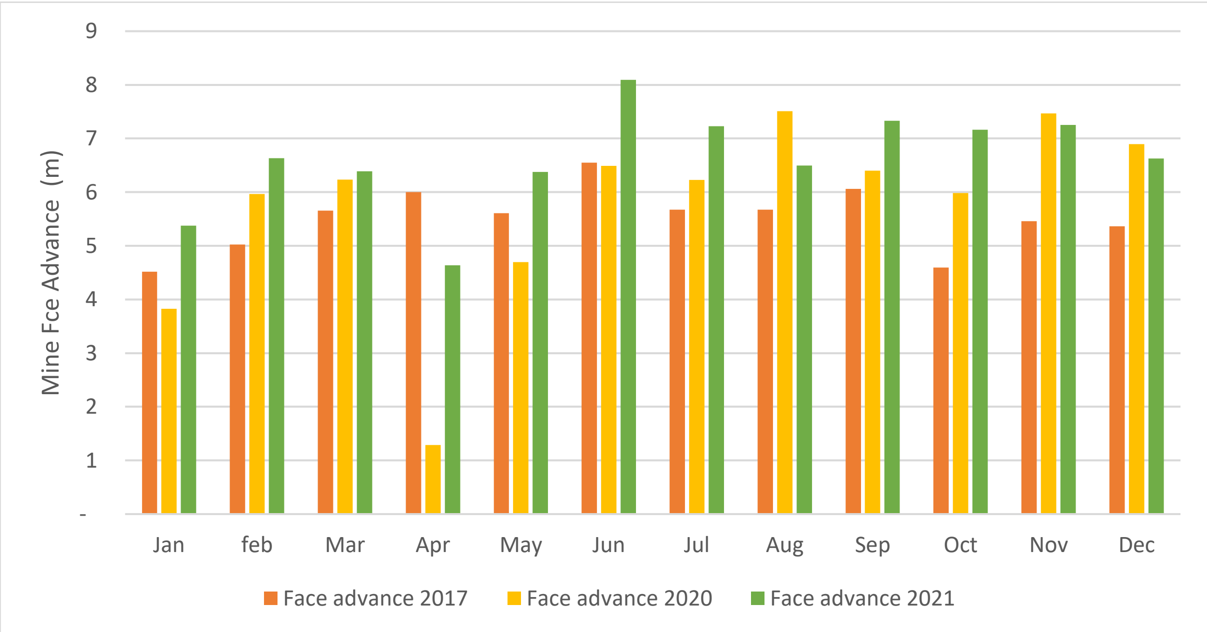

Figure 4.10: Average monthly face advance in 2017, 2020 and 2021 at Ya Rona shaft

Each month was planned according to that year's planning targets. The three analysed years start low in January and increase in February and March. The low face advance in April 2020 was due to the countrywide COVID-19 lockdown, where operations were suspended. The lockdown restrictions were gradually lifted with full operation returning in May 2020. The mine achieved average annual face advance of 5.4 m, 5.7 m and 6.6 m per crew in 2017, 2020 and 2021, respectively.

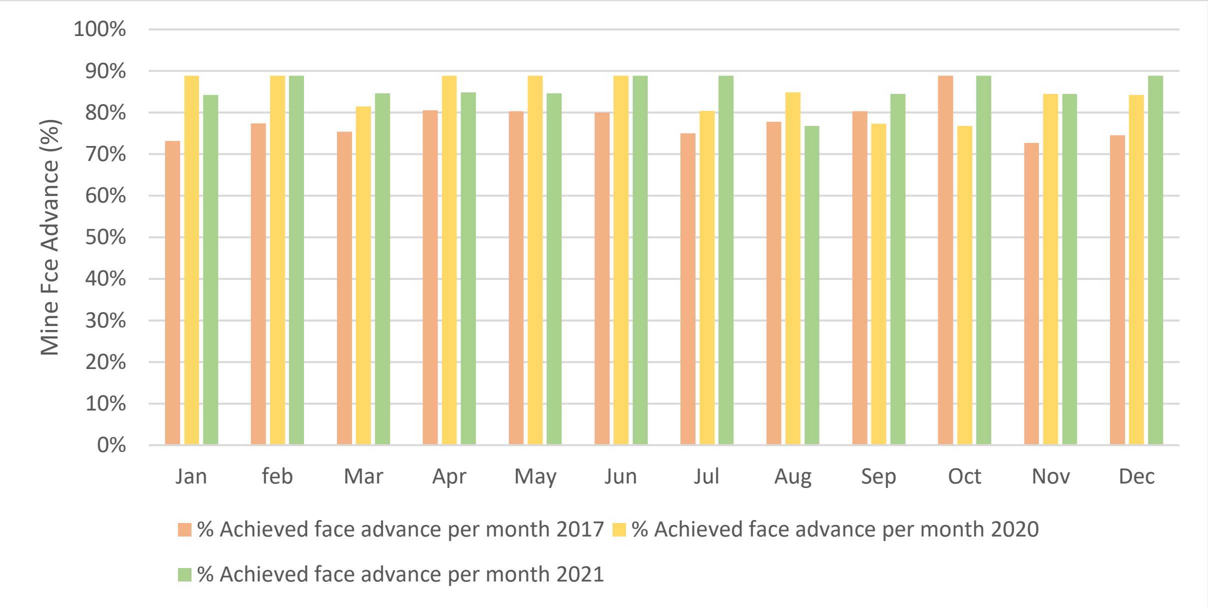

Figure 4.11: Monthly FAA% at Ya Rona shaft

Figure 4.11 shows FAA% in 2017 when cartridge explosives were used and the 2020 and 2021 FAA% when on emulsion explosives were used. The annualised FAA% per crew at the mine in 2017, 2020, and 2021 was 78%, 84%, and 86%, respectively. There was an improvement of 6 to 8 percentage points over the assessed period for emulsion explosives compared to cartridge explosives, with emulsion explosives usage being closest to the FAA% target range of between 90% and 100%.

4.8.2 Hlanganani FAA%

The periods being compared are 2017 until November 2018 when cartridge explosives were used, and 2020 and 2021 when emulsion explosives were used. December 2018 and the whole of 2019 were omitted because the operation was transitioning from cartridge to pumpable emulsion explosives as shown in Figure 4.12. Figure 4.13 shows the corresponding 2017, 2018, 2020, and 2021 FAA%.

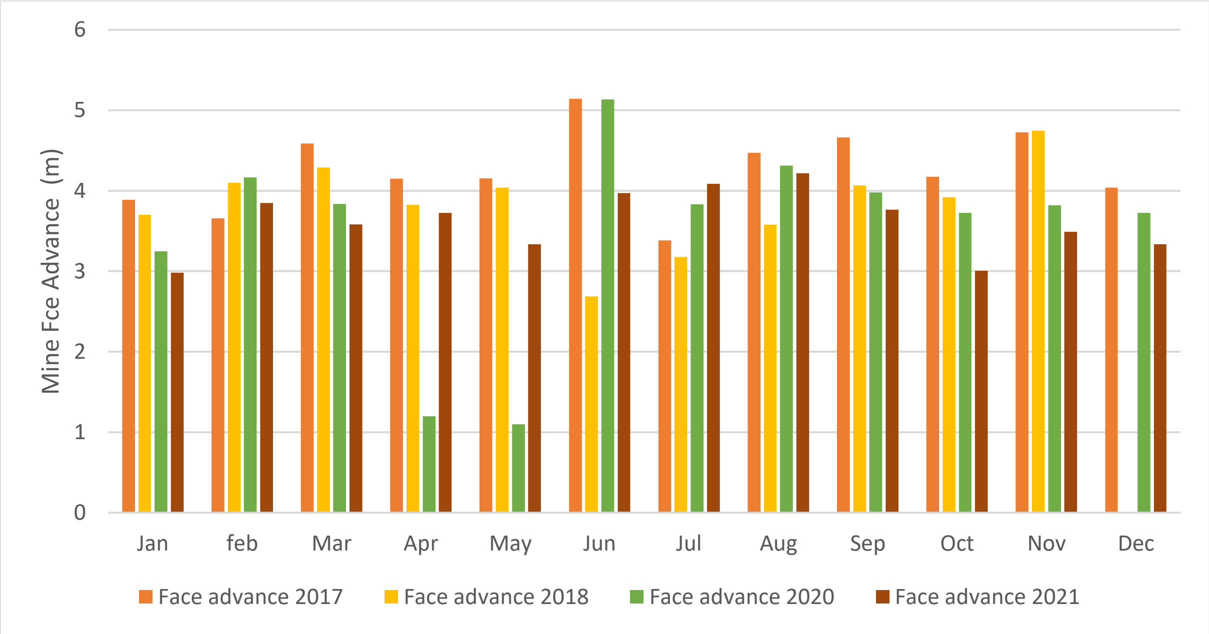

Figure 4.12: Average monthly face advance in 2017, 2018, 2020 and 2021 at Hlanganani shaft

Figure 4.12 shows the results of monthly face advance achieved at Hlanganani shaft. Overall, the face advance was less than 5 m per month irrespective of the explosive type used, but the face advance tended to be slightly better when cartridge explosives were used compared to emulsion explosive. The mine achieved annualised average face advance of 4.3 m, 3.6 m, 3.5 m and 3.6 m per crew in 2017, 2018, 2020 and 2021, respectively. The drop in face advance in April 2020 and May 2020 was due to the COVID-19 lockdown, thus lowering the 2020 average.

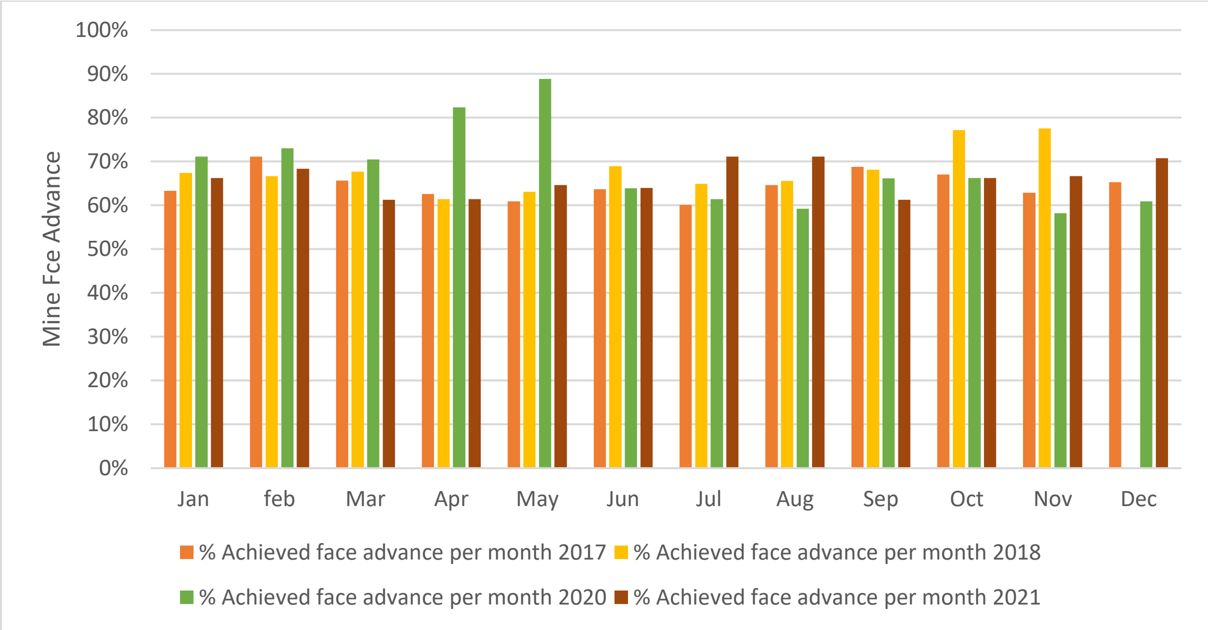

Figure 4.13: Monthly FAA% at Hlanganani shaft

Figure 4.13 shows the 2017 and 2018 FAA% when cartridge explosives were used and the 2020 and 2021 FAA% when emulsion explosives were used. The annualised average FAA% per crew at the mine in 2017, 2018,2020 and 2021 was 65%, 69%, 69% and 66%, respectively. This can be attributed to poor controls at the operation since both explosive types produced significantly below target FAA% results. The higher FAA% in April and May 2020 was due to fewer crews at the mine mining favourable panels.

4.9 Summary

This chapter presented the results collected from Ya Rona and Hlanganani shafts and outlined the comparison approach on the set targets and norms of the selected KPIs, namely, explosives cost, face advance, powder factor, fragmentation, and hangingwall conditions. The chapter started by outlining the operating environment and legal constraints of pumpable emulsion explosives. Then the focus shifted to discuss the results which consisted of primary data, historical data with respect to the aforementioned KPIs. The following chapter presents the analysis of the presented results.

5 ANALYSIS

5.1 Introduction

This chapter presents the analysis of the primary and historical data used in this research. The primary and historical data collected were analysed in the context of KPAs and KPIs outlined in Section 1.5. This chapter starts by providing the analyses of KPIs discussed in Chapter 4, followed by KPA discussion and end by outlining the benefits of the pumpable emulsion explosives.

5.2 Face advance analysis

The overall analysis of the results from both the Ya Rona and Hlanganani shafts points to emulsion explosives being capable of achieving the mine's required face advance of 90% of the blasthole length in narrow reef mining under normal operating conditions. At Ya Rona shaft, 14 out of 20 observed blasts achieved a face advance of over 90% of the blasthole length. At Hlanganani shaft, 12 out of 13 observed blasts from Panels 5, 6 and 7 achieved the expected face advance of between 90% and 100%. The general socket prevalence of less than 4% at Hlanganani shaft is another indication of the capability of the emulsion explosives to achieve the required face advance.

Panel 3 at Ya Rona shaft had an average socket prevalence above the 10% limit due to up-dip mining. The emulsion explosives being used was a non-sticky formulation meant to be used in horizontal or down holes. An up-dip mining can result in the emulsion slumping towards the collar from the toe of the blasthole, living the toe with insufficient product.

5.3 Powder factor analysis

Based on the results in Section 4.5.2, it can be concluded that the planned powder factor for cartridge explosives is higher than the planned powder factor for pumpable emulsion explosives. The actual pumpable emulsion explosives powder factor calculated from the underground measurements can be lower or higher than the corresponding planned powder factor due to in-situ site conditions. To this effect, the three main factors observed that affected the powder factor were:

- a decrease in the mass of explosives due to two rows of blastholes being drilled instead of the prescribed three rows in some panels which resulted in less mass of explosives than planned to be used;
- an increase in the mass of explosives per blasthole due to the pumping of four or five strokes of explosive instead of the required three strokes by some crews which resulted in overcharged blastholes; and
- an increase in the mass of explosives per blast due to an increase in number of holes because of the blast design adjustment.

5.4 Fragmentation analysis

Given the results in Section 4.5.3, it can be concluded that both shafts' target X_{50} was achieved when blast images were analysed with WIPFRAG for both Ya Rona and Hlanganani shafts. Nevertheless, the same cannot be said for X_{50} derived from the images analysed with SPLIT and Kuz-Ram X_{50} prediction for emulsion explosives (expected) and equivalent cartridge explosives, where, in both shafts, the resultant X_{50}s were finer than the target range of 11.5 cm to 13.5 cm. At Hlanganani, the difference between the SPLIT and WIPFRAG, particularly for Blasts No. 6 and 13, is not as pronounced, but is still a concern. The difference in the Kuz-Ram predictions of X_{50} for the expected emulsion and equivalent cartridge explosives was expected due to them being different explosive products; However, the variance for both when compared to the target range, is excessive for both shafts. The reason for the variance can be attributed to the KUZ-RAM prediction's tendency to overestimate the fines fractions (Lawal, 2021).

On the other hand, the difference in the results between SPLIT and WIPFRAG can be attributed to the inherent differences in the two programmes such as the delineation of particles, allocation of particles to size ranges, and the processing of fines (Latham et al., 2003). The two shafts use WIPFRAG for their fragmentation analysis whereas SPLIT, in this research was used for validation purposes. The use of SPLIT for validation purpose can be described as unsuccessful due to the wide variance in the results between the two systems. Notwithstanding, the pumpable emulsion explosive fragmentation KPI assessment is inconclusive based on the results of this research.

5.5 Hangingwall overbreak analysis

The overbreak results at Ya Rona indicated limited damage to the hangingwall and underbreaking in some panels, except for Blasts No. 19 and 20 in Panel 4 where faults were intersected and subsequently exposing the hangingwall lava. The results highlight the influence of rock mass structures on post blast-conditions, which resulted in the overbreak in this case. The underbreaking in general was caused by poor mining practice, rectified by opening up the panel from the bottom to achieve the planned stope width. The analysed results from the observed panels at Hlanganani showed overbreaking in all three observed panels.

Based on the Hlanganani measurements, particularly considering the drilling direction relative to the horizontal plane was 86° and 90°, it can cautiously be concluded that the emulsion explosives can result in overbreaking, though underbreaking can also occur. The results also draw attention to the importance of a blast design adaptation that can effectively respond to changes in geological conditions to minimise the overbreak or damage to the hangingwall.

The burden and drilling direction were included to highlight the blast design application, as non-adherence to these planned parameters can also affects the post-blast conditions. The blasthole burdens generally deviated from planned burden with a variance of less than 10%, except for Panel 1 and Panel 5 at Hlanganani where the measured burdens were varying between 10% and 25% respectively, above the planned burden of 60 cm.

5.6 Explosive costs analysis

The cost comparison of equivalent cartridge, and planned and actual emulsion explosives for each panel of Ya Rona and Hlanganani shafts are summarised in Table 5.1 and Table 5.2, respectively.

Table 5.1: Average cost of explosives per panel at Ya Rona

	Panel 1	Panel 2	Panel 3	Panel 4
Average cost of planned equivalent cartridge explosives (R/m^2)	99.47	100.34	100.34	101.35
Average cost of actual emulsion explosives (R/m^2)	92.57	84.02	65.25	128.59
Average cost of planned emulsion explosives (R/m^2)	74.74	75.39	75.27	76.15

Table 5.2: Average cost of explosives per panel at Ya Hlanganani

	Panel 5	Panel 6	Panel 7
Average cost of planned equivalent cartridge explosives (R/m^2)	100.92	102.11	101.37
Average cost of actual emulsion explosives (R/m^2)	57.24	58.08	85.30
Average cost of planned emulsion explosives (R/m^2)	67.78	68.68	68.18

The cost of actual emulsion explosives compared to the planned emulsion explosives in Panels 1, 2, 3 and 4 in percentage were +24%, +11%, -13% and +31% respectively, with Panel 3 costing the least due to fewer number of blastholes drilled than planned and Panel 4 being the costliest due to overcharging of blastholes. However, the average planned equivalent cartridge explosives cost was still higher than the actual cost of emulsion explosives in Panel 1, 2 and 3 with the exception of Panel 4.

The cost of actual emulsion explosives compared to the planned emulsion explosives in Panels 5, 6, and 7 in percentage where -16%, -15%, and +25% respectively. Panels 5 and 6 cost less than planned because of fewer number of blastholes drilled than planned, and Panel 7 had higher overall cost because of the overcharging of blastholes as well as extra blastholes drilled to reduce the burden due to the increase in the stope width compared to the plan.

The planned cost of equivalent cartridge explosives was higher than the planned pumpable emulsion explosives cost. This points to potential savings that can be realised when the latter type of explosives is used. It can be noted that the planned cost of emulsion explosives can be achieved if blastholes are not overcharged or the charge plan is executed properly. The overcharging of blastholes lead to an increase in the costs of actual emulsion explosives used. The onsite blast pattern adaptation to cater for ground conditions can either increase or decrease the planned number of blastholes, which can also lead to an increase or decrease in the mass of explosives charged compared to the plan.

5.7 Explosive performance

The face advance results showed that pumpable emulsion explosives had a better overall performance at Ya Rona and cartridge explosives had slightly better overall face advance at Hlanganani, noting the negative effect of COVID lockdown on the average face advance achieved in 2020. Ya Rona and Hlanganani shafts achieved an overall average monthly face advance of 5.9 m and 3.8 m respectively, over the period of assessment for both explosive types. The assessment periods were in 2017, 2020 and 2021 for Ya Rona shaft; and 2017, 2018,2020 and 2021 for Hlanganani shaft.

The FAA% results at both operations was lower than the target range of 90% to 100% for all the years analysed for both explosive types. However, Ya Rona was better with an overall average of 83% while Hlanganani achieved 67% when both emulsion and cartridge explosives are considered. Further analysis showed that the emulsion explosives had a better FAA% than the cartridge explosives at both shafts. At Ya Rona shaft the emulsion explosives achieved an average FAA% of 85% compared to 78% for cartridge explosives. Whereas at Hlanganani shaft the emulsion explosives achieved an average FAA% of 67.5% compared to 67% for cartridge explosives. This leads to a conclusion that pumpable emulsion explosives have a better outcome than cartridge explosives and that there is a systemic hinderance to achieving the required face advance at Hlanganani shaft.

5.8 The benefits of pumpable emulsion explosives in narrow reef stopes

The analyses in this chapter were aimed at addressing the research question outlined in Section 1.7 of this report. To answer the research question, the study focused on the three KPAs, namely explosive cost, blasting efficiency, and post blast conditions to quantify the benefits of pumpable emulsion explosives at Ya Rona and Hlanganani shafts. These KPAs are discussed below.

5.8.1 Cost of explosives KPA

The cost of explosives KPA was analysed by comparing the planned and actual explosives cost per centare. It was established that the quantity of emulsion explosives used has a notable effect on the overall explosives cost, consequently influencing the explosives cost per centare. The cost of explosives in this research focused on pumpable emulsion explosives while the cartridge explosives cost was only indicative, that is, in case they were to be used.

According to the analysis, in general, the cost of indicative or planned equivalent cartridge explosives per centare was higher than the cost of both planned and actual emulsion explosives per centare. However, the cost of actual emulsion explosives per centare can be more or less than the planned emulsion explosives per centare if overcharging of blastholes and uncontrolled arbitrary on-site blast pattern adaptation due to face condition take place.

5.8.2 Blasting efficiency KPA

The blasting efficiency KPA was analysed through three KPIs, namely, face advance, powder factor, and fragmentation. The blasting analysis showed that the pumpable emulsion explosives could achieve the required minimum face advance of 90% of the blasthole length under normal operating conditions both at Ya Rona and Hlanganani shafts. The analysis using historical data showed that pumpable emulsion explosives performed better at Ya Rona shaft than at Hlanganani shaft. However, the measurements taken indicated that in general the face advance was acceptable or marginally below the acceptable level at both shafts except for Panel 3 at Ya Rona shaft and Panel 7 at Hlanganani shaft where the face advances were significantly below the target. With respect to the FAA% derived from the historical data, the pumpable emulsion explosives showed better results than cartridge explosives at Ya Rona shaft but the results were inconclusive at Hlanganani shaft. This can be attributed to reasons stated in Sections 5.2 and 5.7.

The powder factor KPI can be influenced by on-site face conditions that can lead to the deviation from the blast design or guidelines. Planned and actual powder factors were different because of the variation in quantities of explosives used. Charging higher quantities of explosives than planned can lead to a finer fragmentation and overbreak. On the other hand, if less quantities of pumpable emulsions explosives than ordered is used, there would be a wastage as unused explosives may be disposed.

The blast fragmentation KPI of pumpable emulsion explosives was evaluated by comparing the Kuz-Ram prediction of expected X_{50} of emulsion explosives and equivalent X_{50} of cartridge explosives X_{50} at both shafts to WIPFRAG and SPLIT image analyses. The image analyses indicated that the X_{50} from the pumpable emulsion explosives is most probably either within both shafts' expected range as indicated by WIPFRAG results or below as indicated by SPLIT results. It also should be noted that both shafts use WIPFRAG to analyse muckpile fragmentation.

5.8.3 Post blast conditions KPA

Post blast conditions of observed blasts where pumpable emulsion explosives were used was analysed using the hangingwall overbreak as a KPI. The analysed results cautiously showed that emulsion explosives have the potential to negatively impact the panel's post-blast condition due to non-adherence to the blast design parameters and the influence of the geological conditions.

5.8.4 Summary of the benefits of pumpable emulsion explosives

With respect to the research question, the benefits of pumpable emulsion explosives in narrow reef stopes based on the outcomes of this research are summarised in Table 5.3.

Table 5.3: The benefits of pumpable emulsion explosives in narrow reef stopes

KPA	Benefit
Explosive cost	• The cost of actual and planned pumpable emulsion explosives is lower than the cost of planned equivalent cartridge explosives. The use of pumpable emulsion is the cost-effective option based on the analysis.
Blasting efficiency	• The analysis of historical data has shown that Hlanganani shaft achieved better face advance with cartridge explosives while Ya Rona shaft achieved better face advance with pumpable emulsion explosives. • In the measurements taken for this research, 92% of the blasts achieved the face advance target at Hlanganani shaft when pumpable emulsion explosives were used, and 70% of the blasts achieved the target face advance at Ya Rona shaft. • The FAA% calculation has indicated that pumpable emulsion explosives can perform equally if not better than cartridge explosives. Using historical data, pumpable emulsion explosives achieved average FAA% of 85% compared to 78% of cartridge explosives at Ya Rona shaft, and both explosive types achieved average FAA% of 67 % at Hlanganani shaft. • Based on the results of this research, pumpable emulsion explosives have achieved X_{50} equal or less than the required X_{50} target range, thereby pointing to a potentially higher grizzly throughput when pumpable emulsion explosives are used while the risk of gold loss due to high percentage of fines is high.
Post blast conditions	• Due to the transient site conditions and the generally slack drilling controls at Ya Rona shaft observed during the course of information gathering, it cannot be concluded whether pumpable emulsion explosives provide better post blast conditions than cartridge explosives.

5.9 Summary

The chapter presented the analysis of results focusing on KPIs outlined in Section 1.5 and in the end highlighted the benefits of pumpable emulsion explosives in narrow reef stopes. It was found that the pumpable emulsion explosives cost less than cartridge explosive on rand per centare basis and provide finer fragmentation with the potential to increase grizzly throughput, but high risk of gold losses. The face advance analyses showed that pumpable emulsion explosives could be better than cartridge explosives, while the powder factor was affected by slack operational controls and site conditions. Lastly, the FAA% was used as an additional measure to analyse the blasting efficiency and it was established that pumpable emulsion explosives were better than cartridge explosives in this regard. The next chapter provides the conclusion and recommendations of this research.

6 CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

This research aimed to prove the efficacy of pumpable emulsion explosives in narrow reef stope mining under non-trial operational conditions and provide unbiased evidence by quantifying the benefits of pumpable emulsion explosives in narrow reef gold mines on carefully selected KPAs of explosives cost, blasting efficiency and post blast conditions. The identified KPAs influence the criteria for selecting explosives.

The KPAs in this research had five corresponding KPIs of explosives cost, face advance, powder factor, fragmentation distribution, and hangingwall overbreak. The objective was to create an understanding of the application of pumpable emulsion explosives in narrow reef stopes of gold mines and establish whether pumpable emulsion explosives are cost-effective compared to cartridge explosives in narrow reef stopes. The narrow reef gold mines used for the study were Ya Rona and Hlanganani shafts, the two operations using emulsion explosives in the stopes since 2018. The primary purpose for using the two mines was to gain insight into the real-life application of pumpable emulsion explosives by noting the experience the crews have on using them.

The literature reviewed for this research mainly looked at the KPIs outlined above. The KPIs were reviewed with respect to factors associated with blast design and optimisation in narrow reef mining and the selection of explosives. The literature review was done to contextualise the research by discussing parameters affecting blasting and selection of explosive types. The main objective of blasting is to achieve productivity and profitability through maximum face advance per length of the blasthole drilled, desired fragmentation and size distribution and it was noted that that the fragments size decreases with an increase in the powder factor. It was also noted that the blast design plays a significant role in the optimal utilisation of explosives and associated costs of explosives by enabling the mine to achieve the required blast outcome and production within the constraints of environmental and operational considerations.

Other important parameters in blasting are blasthole diameter and burden which must be balanced against the possible impact of the blast on the hangingwall in narrow reef mining. In addition to these parameters, the correct selection of explosives and quantity used can lead to enhanced safety, increased productivity and reduced costs.

The research utilised both quantitative and qualitative approaches in methodology to assess the benefits of pumpable emulsion explosives at Ya Rona and Hlanganani shafts. The collected data was categorised into primary and historical data. The historical data was sourced from the central planning department, and the data included planned targets and achieved results before and after the introduction of pumpable emulsion explosives.

The primary data was gathered through underground observations and measurements at Ya Rona and Hlanganani shafts under non-trial conditions. The primary data collected was divided into recorded observations and recorded measurements. Observations were centred on observed drilling and charging practices as well as challenges encountered when using PCU, and measurements recorded included burden, panel width and length, number of blastholes drilled, over- or underbreaks, advance rate and fragmentation. Twenty underground site visits were conducted in four Ya Rona panels, and 13 underground visits were conducted in three Hlanganani panels; each panel was visited four or five times.

The research objectives of creating an understanding of the application of pumpable emulsion explosives in narrow reef stopes of gold mines and establishing whether pumpable emulsion explosives are cost effective compared to cartridge explosives in narrow reef stopes were achieved. Furthermore, the performance of pumpable emulsion explosives was quantified. The results were presented and analysed with respect to each KPA and associated KPIs.

The face advance analysis from the primary data has shown that the pumpable emulsion can achieve set targets, where 92% of the blasts achieved the minimum face advance target at Hlanganani shaft and 70% of the blasts achieved the minimum face advance target at Ya Rona shaft. The prevalence of sockets at Ya Rona and Hlanganani was below the benchmark limit of 10% for all observed panels, except for panel 3 at Ya Rona, which had an average of 19%. The outcome from historical data analysis showed equal or better face advance performance by emulsion explosives over cartridge explosives for the periods assessed at the two shafts. The emulsion explosives showed better performance than cartridge explosives when historical FAA% was analysed.

It was observed that the on-site face conditions influence the miners to deviate from the planned blast design, leading to a change in powder factor as a results of explosives quantity variation. The change in explosives quantity may lead to a finer fragmentation and overbreak, and wastage if explosives less explosives than ordered are used. The blast fragmentation of pumpable emulsion explosives was analysed by comparing the Kuz-Ram prediction of the expected X_{50} of emulsion explosives and equivalent X_{50} of cartridge explosives X_{50} at both shafts to WIPFRAG and SPLIT image analyses. The WIPFRAG image analyses indicated that emulsion explosives achieve the X_{50} target range while the SPLIT analyses of the same images indicated that the

X_{50} was below this range. The SPLIT X_{50} was closer to the predicted Kuz-Ram X_{50} than the WIPFRAG X_{50}.

The hangingwall overbreak was analyses indicated that emulsion explosives could results in overbreak or underbreak. The results showed that other blasting parameters such as ground conditions and blast design execution can influence the hangingwall overbreak or underbreak.

The cost of explosives was analysed by comparing the expenses per centare of planned equivalent cartridge explosives, planned emulsion explosives, and actual emulsion explosives used. The explosives cost per centare changes in line with quantities of explosives used due to overcharging of blastholes and arbitrary on-site blast pattern adaptation due to face condition takes place. The cost of planned equivalent cartridge explosives per centare was higher than the cost of both planned and actual emulsion explosives per centare in general.

The research has shown evidence that emulsions explosives could provide blast outcomes that were within set targets or benchmarks on the observed KPAs. The results showed varying level of achievements across the KPIs when comparing the performance of pumpable emulsion explosives between the two shafts. An overall performance distinction between the two shafts couldn’t be drawn due to the non-comparable analysis outcome of fragmentation, powder factor and hangingwall overbreak KPIs. The research was conducted in non-trial operational settings, where the results could be affected by variations from the planned parameters. These variations might stem from changes in geological conditions, stope width, deviations from blast design, or overcharging of drilled holes. Through the presented results, the study proved the efficacy of pumpable emulsion in narrow reef stope mining under non-trial operational conditions and the benefits of pumpable emulsion explosives in narrow reef gold mines were quantified.

6.1.1 Significance of the research

The research study sought to quantify the benefits of pumpable emulsion explosives in narrow reef under non-trial operational conditions. Pumpable emulsion explosives benefits were quantified through the analyses of explosives costs, blast efficiency and post blast conditions KPAs. The explosives cost KPA analysis showed that pumpable emulsion is cost effective. The blast efficiency KPA analysis has indicated that pumpable emulsion can achieve better face advance than cartridge explosives, achieve the mine's set target. This was corroborated by historical FAA% calculations. The pumpable emulsion explosives achieved equal or less than the X_{50} target range.

The benefits highlighted in the research are significant to narrow reef gold mining in South Africa as the outcome can guide the mines to make an informed decision when selecting the explosives type.

6.2 Recommendations

The scope of this research was limited to the blast designs of Ya Rona and Hlanganani shafts. Further research beyond this scope should be considered, to include other operations as the use of pumpable emulsion explosives spreads to ascertain if similar or better results can be achieved, in particular with respect to the face advance.

The results of this research can be enhanced by a study that will focus on fragmentation, where different fragmentation analysis computer programmes are used to ascertain the benefits of pumpable emulsion explosives, followed by validation through sampling. Furthermore, a study on the extent of hangingwall damage using advanced ground survey technology or other technologies must be conducted to ascertain the extent of damage when using emulsion explosives in different ground conditions.

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8 APPENDICIES

Appendix 5: Face advance calculations on Ya Rona primary results

Panels	Blast no.	Planned stope width	Average actual S/W	SW width overbreak	Expected advance (m)	Actual measured advance (m)	Plan vs actual	Average sockets (m)	Sockets prevalence per blast
Panel 1	1	220	187	-33.0	0.9	0.9	0.0	0.1	5%
	2	220	220	0.0	0.9	0.9	0.0	0.1	6%
	3	220	206	-14.0	0.9	0.8	-0.1	0.1	3%
	4	220	213	-7.0	0.9	0.9	0.0	0.1	4%
	5	220	217	-3.0	0.9	0.9	0.0	0.2	5%
Panel 2	6	180	198	18.0	0.9	0.8	-0.1	0.1	4%
	7	180	165	-15.0	0.9	0.8	-0.1	0.1	4%
	8	180	164	-16.0	0.9	0.9	0.0	0.2	2%
	9	180	186	6.0	0.9	0.9	0.0	0.0	0%
	10	180	183	3.0	0.9	0.9	0.0	0.1	1%
Panel 3	11	180	168	-12.0	0.9	0.6	-0.3	0.5	17%
	12	180	176	-4.0	0.8	0.6	-0.2	0.4	15%
	13	180	173	-7.0	0.9	0.6	-0.3	0.3	22%
	14	180	177	-3.0	0.9	0.6	-0.4	0.4	20%
	15	180	181	1.0	0.9	0.7	-0.2	0.2	19%
Panel 4	16	180	194	14.0	0.9	0.9	0.0	0.2	2%
	17	180	169	-11.0	0.9	0.8	-0.1	0.3	4%
	18	180	184	4.0	0.9	0.7	-0.2	0.3	7%
	19	180	203	23.0	0.9	0.8	-0.1	0.2	4%
	20	180	210	30.0	0.9	0.8	-0.1	0.1	6%

Appendix 6: Face advance calculations on Hlanganani primary results

Panels	Blast no.	Planned stope width	Average actual S/W	SW width overbreak	Expected advance (m)	Actual measured advance (m)	Plan vs actual	Average sockets (m)	Sockets prevalence per blast
Panel 5	1	135	178	43.0	0.9	0.9	0.0	0.1	2%
	2	135	178	43.0	0.9	0.9	0.0	0.1	1%
	3	135	130	-5.0	0.9	0.9	0.0	0.0	1%
	4	135	130	-5.0	0.9	0.9	0.0	0.1	2%
	5	135	165	30.0	0.9	0.9	0.0	0.1	2%
Panel 6	6	142	172	30.0	0.9	0.9	0.0	0.1	2%
	7	142	172	30.0	0.9	0.9	0.0	0.0	2%
	8	142	182	40.0	0.9	0.8	-0.1	0.2	2%
	9	142	175	33.0	0.9	0.8	-0.1	0.1	3%
Panel 7	10	214	232	18.0	0.9	0.7	-0.2	0.2	4%
	11	214	232	18.0	0.9	0.8	-0.1	0.1	2%
	12	214	220	6.0	0.9	0.9	0.0	0.1	3%
	13	214	225	11.0	0.9	0.9	0.0	0.1	3%

Appendix 7: Calculations on mass of explosives, powder factor and analysed images particle size for Ya Rona

	Mass of explosives							Powder factor			Kuz Ram mean particle size (cm)		Particle size (X50) from analysed images (cm)	
B*	Planned production mass per hole cartridge (kg)	Planned production mass per hole emulsion (kg)	Average actual mass production per hole emulsion (kg)	Number of production holes charged	Planned total explosives cartridge (kg)	Planned explosives charged emulsion (kg)	Total explosives charged emulsion (kg)	Planned powder factor cartridge kg/m³	Planned powder factor emulsion kg/m³	Actual powder factor emulsion kg/m³	Calculated X50-planned cartridge (cm)	Calculated X50-planned emulsion (cm)	SPLIT X50 results (cm)	WIPFRAG X50 results (cm)
1	0.69	0.60	0.6	78	53.81	46.80	46.80	1.87	1.63	1.63	5.75	7.30		
2	0.69	0.60	0.6	72	49.67	43.20	43.20	1.79	1.56	1.56	5.96	7.57		
3	0.69	0.60	0.6	72	49.67	43.20	43.20	1.79	1.56	1.56	5.96	7.57	7.48	14.10
4	0.69	0.60	0.8	70	48.29	42.00	56.00	1.74	1.52	2.02	6.10	7.74		
5	0.69	0.60	0.8	80	55.19	48.00	64.00	1.92	1.67	2.23	5.63	7.15		
6	0.69	0.60	0.6	91	62.78	54.60	54.60	2.04	1.77	1.77	5.37	6.82		
7	0.69	0.60	0.8	93	64.16	55.80	74.40	2.03	1.77	2.36	5.39	6.85	5.73	13.63
8	0.69	0.60	0.8	95	65.54	57.00	76.00	2.16	1.88	2.51	5.13	6.51		
9	0.69	0.60	0.6	74	51.05	44.40	44.40	1.97	1.71	1.71	5.53	7.02		
10	0.69	0.60	0.6	74	51.05	44.40	44.40	1.97	1.71	1.71	5.53	7.02		
11	0.69	0.60	0.6	69	47.60	41.40	41.40	1.84	1.60	1.60	5.84	7.42		
12	0.69	0.60	0.6	67	46.22	40.20	40.20	1.73	1.50	1.50	6.13	7.79		
13	0.69	0.60	0.6	64	44.15	38.40	38.40	1.70	1.48	1.48	6.21	7.88		
14	0.69	0.60	0.6	75	51.74	45.00	45.00	1.77	1.54	1.54	6.01	7.63		
15	0.69	0.60	0.6	75	51.74	45.00	45.00	1.73	1.50	1.50	6.14	7.80	3.58	12.84
16	0.69	0.60	1	88	60.71	52.80	88.00	1.50	1.30	2.17	6.87	8.73		
17	0.69	0.60	1	149	102.79	89.40	149.00	2.54	2.21	3.68	4.51	5.73		

18	0.69	0.60	1	148	102.10	88.80	148.00	2.52	2.19	3.65	4.54	5.76	5.94	12.81
19	0.69	0.60	0.8	145	100.03	87.00	116.00	2.47	2.15	2.86	4.61	5.85		
20	0.69	0.60	0.8	145	100.03	87.00	116.00	2.57	2.24	2.98	4.46	5.67		

*Blast no.

Appendix 8: Calculations on mass of explosives, powder factor and analysed images particle size for Hlanganani

	Mass of explosives							Powder factor			Kuz Ram mean particle size (cm)		Particle size (X50) from analysed images (cm)	
B*	Planned production mass per hole cartridge (kg)	Planned production mass per hole emulsion (kg)	Average Actual mass production per hole emulsion (kg)	Number of production holes charged	Number of production holes planned	Planned total explosives cartridge (kg)	Total explosives charged emulsion (kg)	Planned powder factor cartridge kg/m³	Planned powder factor emulsion kg/m³	Actual powder factor emulsion kg/m³	Calculated X50-planned cartridge (cm)	Calculated X50-planned emulsion (cm)	SPLIT X50 results (cm)	WIPFRAG X50 results (cm)
1	0.69	0.60	0.6	85	107	58.64	51.00	2.19	1.91	1.91	5.07	6.44		
2	0.69	0.60	0.6	84	107	57.95	50.40	2.17	1.89	1.89	5.12	6.50		
3	0.69	0.60	0.6	85	97	58.64	51.00	2.41	2.10	2.10	4.70	5.96	5.08	11.69
4	0.69	0.60	0.6	92	102	63.47	55.20	2.49	2.16	2.16	4.58	5.82		
5	0.69	0.60	0.6	85	102	58.64	51.00	2.30	2.00	2.00	4.88	6.20		
6	0.69	0.60	0.6	122	172	84.16	73.20	1.88	1.64	1.64	5.73	7.28	8.49	11.31
7	0.69	0.60	0.6	126	172	86.92	75.60	1.94	1.69	1.69	5.59	7.09		
8	0.69	0.60	0.6	132	172	91.06	79.20	2.04	1.77	1.77	5.38	6.83		
9	0.69	0.60	0.6	210	187	144.87	126.00	2.98	2.59	2.59	3.96	5.03		
10	0.69	0.60	0.8	142	122	97.96	113.60	2.03	1.77	2.36	5.38	7.17		
11	0.69	0.60	0.6	138	122	95.20	82.80	1.98	1.72	1.72	5.51	6.99		
12	0.69	0.60	0.6	148	122	102.10	88.80	2.12	1.84	1.84	5.21	6.61		
13	0.69	0.60	0.6	141	122	97.27	84.60	2.02	1.76	1.76	5.41	6.87	8.63	9.73

*Blast no.