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EVALUATING THE ECONOMICS OF CONSTRUCTING MINE HAUL ROADS USING PORTLAND CEMENT STABILIZATION- A CASE STUDY AT LUMWANA MINE

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A research report submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, Johannesburg, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

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"Whenever you find yourself doubting how far you can go,
just remember how far you have come"

Unknown

ABSTRACT

Surface mine operations engage in various strategies to optimise efficiency and productivity. The efficiency and productivity aspect of such operations aims to deliver the maximum amount of mined tonnes out of the open-pit using minimum resources. Efficiency and productivity entail that the means of conveying the material mined out of the open-pit must be at their best. In turn, equipment used in mining must be available in a good state. Furthermore, the road network and the bench conditions where such equipment operates in must offer minimum resistance for efficient utilisation.

In this study, a means of improving the mine haul road condition was examined in which a ramp section at Barrick's Lumwana Mine in North Western Zambia was stabilised with Portland cement to make it competent with an extended life span. The 300 m of Portland cement stabilised ramp section provided a common overlap of information before and after stabilisation. The information was then used as input for this study. The ramp was observed for data collection over six months, from June 2020 to December 2020. MaxMine, an independent fleet management and optimisation system, was used to collect truck-related information such as speed, time through the section, distance travelled, entry speed, the payload in tonnes, fuel consumption, and surface smoothness of the haul road section. An analysis of this information was able to deduce gains made in fuel usage, truck loaded haul and empty speeds, payload, and haul road smoothness.

Information on the construction costs and other input parameters related to haul road maintenance was consolidated from the mine's project office and used as input data. The research study deduced that cement stabilisation delivered value in the productivity and efficiency of the mine operation as there was a 12% increase in the haulage speed of loaded trucks and a 45% increase in the empty return leg.

Even though the maximum allowable empty truck speed is 50 km/h on the mine haul roads, going down the ramp is restricted to 30 km/h and the recorded speed in the study of 34 km/h showed that a smooth ramp can be a source of safety violations. The mine has since installed a fleet management system to monitor and manage speed violations and invested in simulator training for its operators to ensure they drive the trucks within safe allowable speed limits using installed systems on the haul trucks such as the speed retarder and cruise controls.

There was a 10% reduction in fuel consumption on the loaded haul and 14% on the empty return. There was also a corresponding payload increase of 5% from 243 tonnes to 255 tonnes for the review period. The increase in payload was within the capacity of the tyres to handle and had no negative impact on tyre life as the 53/80R63 tyres fitted on these trucks can handle more than 255 tonnes of payload. It is the same tyre specification used on a Hitachi 5000AC-3 dump truck that carries a nominal payload of 296 tonnes The ramp section in the research study delivered an overall value gain of over $306,000 despite incurring additional road construction costs of 13% above the normal. The additional construction costs were offset by the gains made on reduced haul road maintenance costs, which were reduced by 99.5%. Other gains made were on fuel consumption and truck maintenance through hours saved from truck speeds/cycle time gains.

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviation	Description
ADT	Articulated Dump Truck
ANN	Artificial Neutral Network
CBR	California Bearing Ratio
CW5	Chimiwungo West stage 5 pit at Lumwana Mine
DCP	Dynamic Cone Penetration
FELA	Fatigue Equivalent Load Analysis
GA	Genetic Algorithm
GPS	Global Positioning System
HRC	Haul Road Condition
NGL	Natural Ground Level
OEM	Original Equipment Manufacturer
PI	Plasticity Index
PLM	Payload Management System
RAC	Road Analysis Control
RMS	Root Mean Square
ROM	Run-of-Mine
UCS	Uniaxial Compressive Strength

Symbol	Description	Units
$	United States of America dollar	currency
km/h	Kilometre per hour	speed
m	meter	distance
t	Tonne	mass
lb	Pound	mass

1 INTRODUCTION

This study will evaluate the economics of constructing mine haul roads using Portland cement stabilisation. This study will assess the economic benefits realised in constructing mining haul roads, particularly ramps, with the Portland cement stabilisation method by quantifying input costs and realised benefits for the duration of use. The study will involve a case study of Barrick Lumwana Mine’s Chimiwungo (Chimi) West 5 (CW5) ramp sections.

1.1 Research Background and Context

Mining haul roads are an essential part of the production cycle in open-pit operations. The integrity of the mine haul road network influences the productivity and efficiency of such an operation as it directly bears the critical cost and productivity metrics such as tyre life, fuel efficiency, cycle time, and structural condition of haul trucks.

Industrial Psychology Consultants (2017), defined productivity as concerned with producing output efficiently through a process that explicitly addresses the inputs used to make the output. Such a process establishes the relationship between what comes out of the organisational system regarding quality products and services that satisfy human needs and what goes into the organisational system regarding the resources consumed to generate those products and services. Productivity in mining is of high significance as it creates an environment that enables mining houses to mine efficiently and keep to the lower end of the industry cost curve. Furthermore, mining is a commodity business whose main outputs are homogenised products; producers have little freedom to boost the value of their output in terms of product differentiation or branding. Therefore, productivity remains a vital attribute of an operation that will make it sustainable through the various cycles of a mine’s life (Humphreys, 2020).

Moreover, mineral commodities suffer more constraints in their marketing as they are traded on international commodity trading houses that determine the price. Metals, therefore, fall into the category of price takers, defined, according to Hayes (2020), as individuals or companies that accept prevailing prices in a market due to, lack of market share to influence the market prices on their own. In addition to the constraints mentioned above, Monitor Deloitte (2016), further acknowledges that the mining industry in Africa is faced with other challenges, such as declining grades, substantial labour unrest, and loss of a significant share of the global market. Getting around such challenges requires the industry to innovate as a way of driving productivity and overall long-term competitiveness

Mine haul road networks are integral to the open-pit production and innovation cycle. Any inefficiency resulting from an underperforming haul road will immediately impact a mine’s productivity and cost. Therefore, a mine haul road network is one significant unit of infrastructure that plays an essential role in unlocking value. In addition, the mine haul road network directly influences the operation's productivity, equipment availability, and safety of a mine’s operations as the trucks and all mobile equipment interact with one another on the haul roads. As a result, haul roads must be designed and built to enhance productivity and efficiency in the performance of a mine operation.

Thompson (2017), acknowledged that a well-built and maintained haul road enables haul trucks' efficient and safe operation. A poor haul road network is a hazard to haul truck operators and other mobile equipment users. Thompson (2017), summarised the advantages of a well-designed, built, and maintained haul road to a mine operation as follows:

- The creation of a safe hauling environment, thereby reducing traffic-related hazards and incidents;
- Increased productivity at a lower cost per tonne hauled as a result of faster cycle times and reduced operating costs;

- Reduced haul road maintenance costs, less spillage of loaded material from the trucks, less dust generated, improved drainages and water management, resulting in longer haul road service life; and
- Improvement in tyre/rim life.

Thompson (2017), further acknowledged that many mining operations rely heavily on local experience in building haul roads and use empirical methods to develop designs and construction methods. This method has often delivered the desired results, as the built haul roads have been adequate. However, such a process does not allow for understanding the design process and identifying the underlying root causes in the event of the sub-standard performance of a haul road. The design and subsequent construction of haul roads using empirical methods is generally considered unsatisfactory as it has the potential to cause excessive expenditure due to:

- Over-design and specification can cause a higher initial cost of construction which sometimes is spent on short-term, low-volume haul roads; and
- Under-design and consequently under-expenditure, causing premature failure of the haul road.

Under-designed roads result in an intensive maintenance regime which causes a lot of mine resources to be committed. As a result, under-designing leads to postponed scheduled maintenance on well-constructed haul roads, which causes them to perform poorly due to mine resources being committed to the intensive maintenance requirements of the under-designed haul roads. Consequently, under-expenditure on haul roads leads to premature failure, excessive truck operating costs, loss of productivity, and resultant high costs attributed to rolling resistance when it comes to long-term high volume roads (Thompson, 2017).

The urge to maximise the economy of scale in mine material movements and the increase in truck payloads has resulted in a population increase of 40% in the giant ultra-class haul trucks of more than 220 tonnes of all used mine haul trucks. These increases in size and volume tend to impact the performance of mine haul roads. The poor performance of haul roads then increases the overall mine operating costs directly or indirectly in terms of production loss incurred due to low equipment availabilities and production inefficiencies induced by poor haul road networks (Thompson, 2017).

Mining operations employ various methods and strategies to construct and sustain these haul roads to levels where they deliver desired results. The haul roads have to be robust enough to carry heavy loads of as much as 500 to 600 tonnes in gross weight and be fit for use in wet conditions during rainy seasons (Tannant & Regensburg, 2001).

The mining operation uses waste rock from their pits in layers as deep as two to four meters to build desirable and robust haul roads. However, due to the heavy loads involved, the resulting roads built are challenging to maintain, and time and again, the top one to two meters must be ripped off and replaced. This situation worsens if the characteristics of available run-of-mine (ROM) material from the mining operation are composed of material with low compressive strength (Douglas, 2021).

The resulting high maintenance regime required to keep such haul roads in good shape hurts mine operations' productivity. For example, many grader hours are needed to skim off soft sections and smoothen off undulations constantly. This is also due to a high-cost of resurfacing program that has to be employed. Moreover, the rolling resistance of the road surface tends to increase with an increase in rough and soft sections, which increases fuel burn rates and cycle times and diminishes tyre life (Global Road Technology, 2022).

1.1.1 Haul road construction at Lumwana Mine

Lumwana Mine is a copper mine that runs as a conventional open-pit (truck and shovel) operation. It is located about 100 kilometres west of Solwezi in Zambia, one of the most prospective copper regions in the world. The ore from the Lumwana Mine, predominantly sulfide, is treated through a conventional sulfide flotation plant, producing copper concentrate (Barrick Gold Corporation, 2011). Figure 1-1. shows the location of the Lumwana Mine.

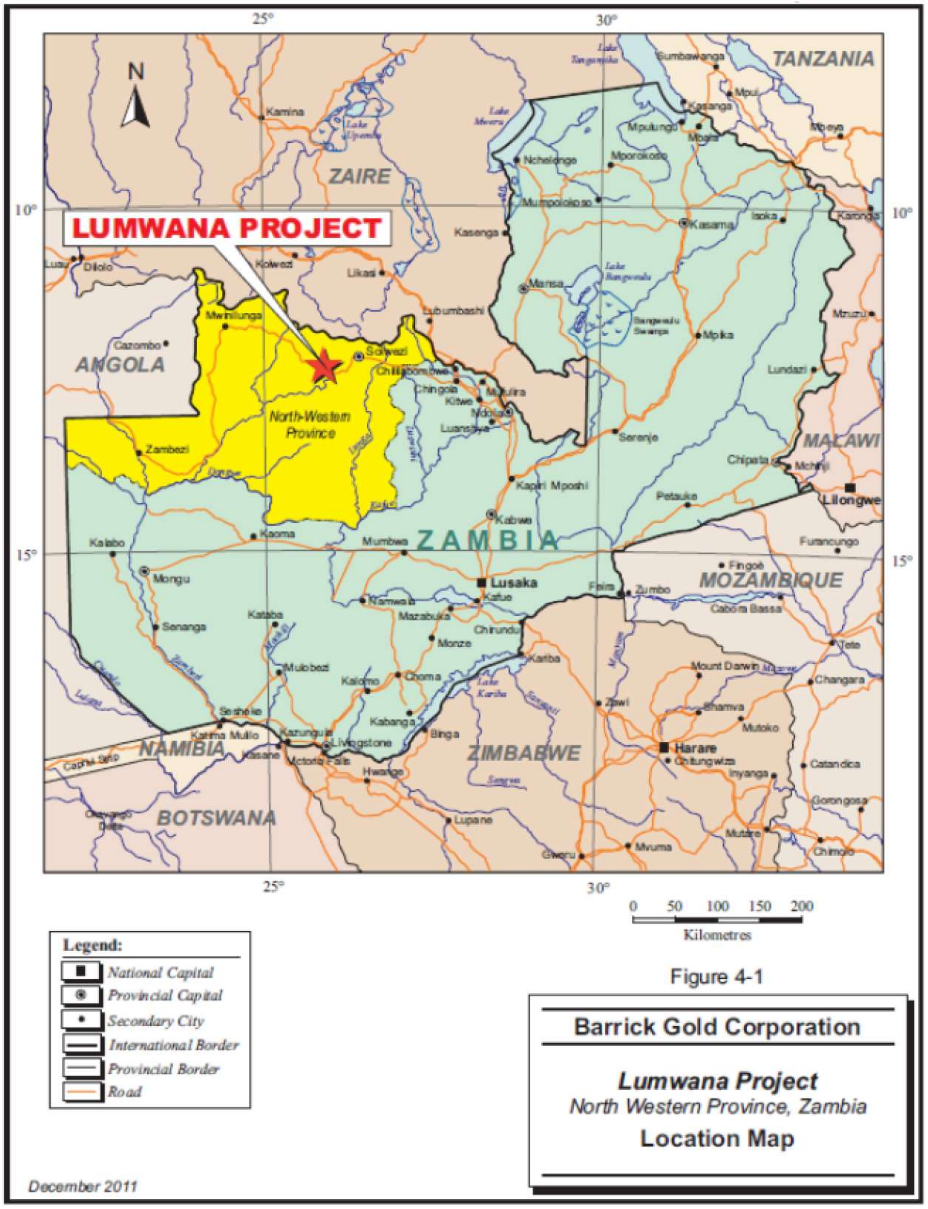


Figure 1-1. Location map of Lumwana Mine (Barrick Gold Corporation, 2014).

The mine uses hydraulic shovels ranging from $15m^3$ to $42m^3$ to load its 31 Hitachi EH4500 haul trucks, upgraded to 290t net payload. Full production began in 2008, with the mine hauling an average 260kt of material per day, with 20% of its material, composed of saprolite overburden, moved by a contractor (Barrick Gold Corporation, 2014).

Lumwana Mine has complex geology lying in the Mwombezi Dome. This a basement dome trending north east in the Neoproterozoic Lufilian Arc Thrust Fold Belt. The geology consists of high-grade metamorphosed and intensely mylonitised, recrystallised schists. However, within the schists are localised occurrences of a pink gneissic material with similar mineralogy to the schists but generally somewhat more felsic (and less micaceous) and harder. This geology affects the quality, consistency, and workability of the potential materials for road construction (SRK Consulting, 2013). The mine recently restarted its basalt rock borrow pit to supply very competent road building material in its Chimiwungo pits where the available rock is not very competent. This borrow pit sits on the mining lease about 10 km away from the nearest pit.

The roads in Lumwana are currently constructed using the ROM competent waste material from the open-pit, which is placed in layers of 1m to 4m of sub-base material compacted using haul trucks and compactor rollers. The base is a 300 to 500mm layer of 100mm crushed rock with a running surface constructed of a thin layer of less than 50mm of crushed rock. Compaction is done in succession using haul trucks and compactor rollers, which are usually effective, especially for the top finish layers.

Recently, the mine embarked on a project to use the cement stabilisation method to construct some of its critical haul roads and ramps to get better quality and durable haul roads. This technique works well for haul roads that have been done using the ordinary ROM competent gneiss material and is doing much better for roads constructed with imported basalt rock material (Lumwana mine b, 2020).

1.2 Key Definitions and Abbreviations in Mine Haul Road Construction

This section defines key terminologies and abbreviations used in mine haul construction. These terminologies and abbreviations will be used in this report in various sections.

- **Surface/wearing/running course**-This is the uppermost surface of the haul road which comes into contact with the tires. Among other properties, such as reducing the dust emitted and giving the haul road a smooth finish, the layer also reduces the stress on the base by distributing the load evenly (Kumar, 2000);
- **Base layer**-This is the layer directly beneath the wearing course providing the main structural strength of the haul road. This layer is usually constructed with high-quality material of a particular particle size distribution (Kumar, 2000);
- **Sub-base layer**-This is the layer of road between the subgrade and the base of the road, which serves several purposes, such as providing structural strength of the haul road and preventing intrusion of the subgrade into the base layer and vice versa (Kumar, 2000);
- **Subgrade layer**-This is the naturally occurring in-situ surface on which a haul road is built. This layer can sometimes consist of previously placed rock, soil, or mine spoil (Kumar, 2000);
- **Rolling resistance**-The energy loss per distance travelled by a vehicle due to non-elastic deformations of the tires and failures in the wheel suspension system (Andersen, et al., 2015). It is further defined as a vehicle's energy required to maintain a constant speed over a running surface. (Bridgestone Americas Tire Operations, 2020);
- **Dynamic Cone Penetration (DCP)**-A testing method through which the strength of in-situ soil and the thickness and location of subsurface soil layers is measured (Applied Research Associates-Vertek, 2015);

- **California Bearing Ratio (CBR)**-is a measure of the soil strength, determined from the load required to cause a plunger of a standard size to penetrate the compacted soil surface, expressed as a percentage of an expected value (SRK Consulting, 2013).

1.3 Problem Statement and Research Question

Mining operations employ various strategies for increasing profit margins. They do this because the industry faces several challenges which can erode profitability. Therefore, the urge to be efficient is not optional, as inefficient operations find themselves on the higher end of the industry cost curves and are the first to be affected by any turbulence that negatively affects the economics of the mining industry.

Higher productivity in mining operations has an immediate positive impact on the mining unit cost. The more tonnes a mine operation hauls out of the mine, the more likely it is to maintain a lower unit mining cost. However, moving more tonnes out of a mine requires larger trucks carrying larger loads of ROM material. This situation causes undue strain on mine haul road networks requiring them to be built differently. Robust and well-maintained haul roads become an essential strategy in achieving this. Such haul roads contribute to shorter cycle times, increasing productivity and saving fuel costs, tyres, and grader hours. Engineered solutions are, therefore, developed to overcome challenges that cause haul roads to fail.

At Lumwana Mine's Chimiwungo open pit, challenges with the haul roads include rapid disintegration due to heavy loads, weak structural properties of ROM material, and prolonged wet conditions. Some sections of such haul roads will at some point impact production as they do not support smooth running of traffic due to trucks consistently getting stuck. To best overcome the above-highlighted challenges at Lumwana Mine leads to the research question:

"Is constructing mine haul roads using Portland cement stabilisation an economical option at Barrick Lumwana Mine?"

1.4 Justification for Research

The mechanisation of mining operations has changed the landscape of most African mining operations. Several projects that would otherwise not be feasible have been operationalised owing to the ability to mine in large volumes, taking advantage of economies of scale principles. Some of these operations would have otherwise not been profitable due to low grades, but with enhanced capabilities to mine large quantities, it's now feasible to run such projects efficiently. Mining operations have to construct robust haul roads to support the large tonnages moved using huge trucks to match the level of innovations and efforts made to raise productivity in the mining industry.

Since its merger with Randgold in 2019, Lumwana Mine embarked on an aggressive program to improve its efficiency by increasing its productivity and reducing its unit cost. Figure 1-2 shows the net direct costs also referred to as C1 production unit costs for the mine over three years. These are cash costs incurred in the mining value chain from mining to processing until the recovered metal is delivered to the market (Mining and Processing Solutions , 2016).

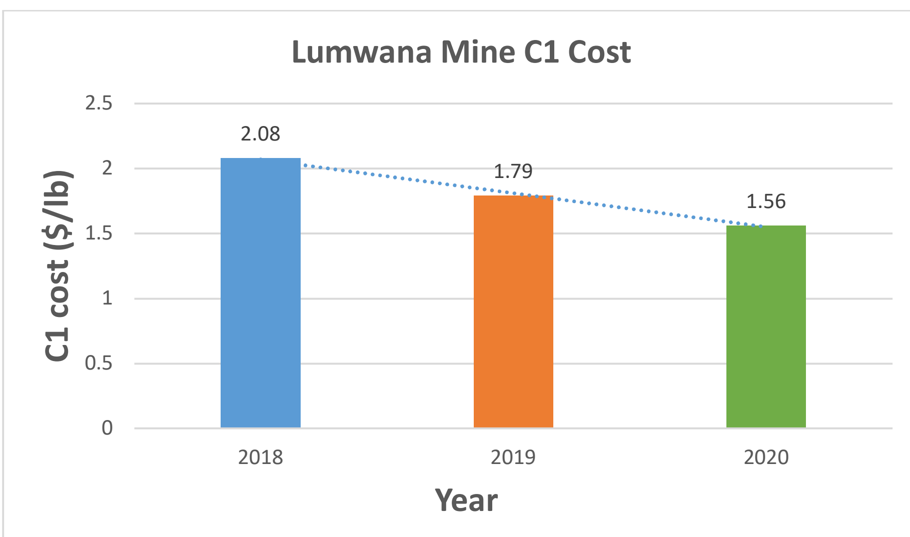


Figure 1-2. Lumwana Mine C1 production unit cost 2018 to 2020 (Barrick Gold Corporation, 2021)

From Figure 1-2, the production unit C1 cost for the mine showed a downward trend resulting in a 25% cost reduction between 2018 and 2020. For the same period, the all-in sustaining unit costs, which is the costs of sustaining the mine operation and includes all the costs of production (C1 inclusive) plus sustaining capital costs, showed a downward trend starting at $3.08/lb in 2018 and closing at $2.43/lb in 2020 (Barrick Gold Corporation, 2021). Achieving this downward trend in cost required several initiatives to be outlined with systematic steps implemented to achieve the changes. Some of these step-changes needed an increase in productivity at a lower cost. On the operation's mining load and haul side, this called for mine haul roads to be in their best condition to support this aggressive ramp-up in productivity while keeping costs to a minimum.

Lumwana Mine has had challenges in building low-maintenance roads in its Chimiwungo pits. The other pits in Malundwe area about 14 km apart have a different geology and more competent rock hence do not suffer this problem. The challenge in Chimiwungo is because the material found in this part of the mine is of low compressive strength and disintegrates rapidly once heavy trucks start running on it. The situation worsens when this material mixes with water from rain or dust suppression water carts as it swells up and rapidly gives in. Therefore, this calls for repeated grading to skim off the top layers every shift to maintain a motorable haul road surface. The result is a high road maintenance regime that demands enormous resources in grader hours and road resurfacing programs as quantified in Chapter 4 of this research.

Given the above situation and the urge to get better results from the haul roads that support high productivity at low-cost, mine operations drive initiatives that build robust haul roads using a combination of materials that may not have been successfully used before. One such initiative was to build roads that overcame the limitations of the unavailability of suitable haul road construction material in the vicinity of the mine using the Portland cement stabilisation method. This study, therefore, offers a qualitative and quantitative analysis of this approach to building haul roads to understand how economical this approach is.

1.5 Research Objectives

The research aims to determine how cost-effective haul road construction using Portland cement stabilisation at Barrick Lumwana open-pit mine is. The objectives of the study are to:

- Do a literature review on Portland cement stabilisation in haul road construction and the economics of haul roads in a mine operation;
- Analyse the economic benefits realised from pit ramps constructed with Portland cement stabilisation compared with sections of haul roads before cement stabilisation;
- Establish suitable parameters in which Portland cement stabilisation can successfully be used at Lumwana Mine; and
- Summarise the research's key findings, making suitable recommendations relevant to improving the way mine haul roads are constructed across the mining industry.

1.6 Research Scope

The scope of this study is to do a cost analysis of constructing mine haul roads using Portland cement stabilisation. It will cover an analysis of practical cost effective ways Portland cement stabilisation can be used in building haul roads at Barrick Lumwana Mine. This is because a section of pit ramps of about 299 metres was constructed using cement stabilisation. The haul road section was opened up to mine haulage traffic for not less than six months, and its condition was monitored during the same period.

The applicable maintenance applied to the haul sections during this period was considered, and the study analysed their construction and maintenance costs. The analysis covered the realised benefits throughout the study. Detailed technical information on the cement stabilised ramp section's construction specifications was outside this study's scope. Therefore, the only details provided were high-level technical construction specifications.

1.6.1 Qualitative Research

The study applied qualitative research methods through a literature review of related topics. This addressed what was previously done in this area of study. In addition, the study further reviewed where such studies were conducted and drew lessons relevant to this research.

Qualitative data from the Mining Projects Department, such as haul road maintenance regimes/schedules and construction methodologies formed part of the research process as such data was input for quantitative analysis.

1.6.2 Quantitative Research

Quantitative research methods was applied using haul road construction and maintenance data from the Barrick Lumwana Mine projects office. The study further computed various finance related metrics such as fuel, maintenance, payload, speed and cycle time gains. In addition, the study utilised technologically enhanced mining fleet management solutions to provide further quantitative data input.

1.7 Sources of Data

The study obtained data from the Mining Projects Department of Barrick Lumwana Mine, utilised geotechnical measured data to determine the technical properties of the constructed haul road section after the application of Portland cement stabilisation. Furthermore, the research utilised the MaxMine data sources to obtain the haul truck counts, average speeds, travel times, common distance travelled, payloads, throttle status and the fuel used. The MaxMine system further gave haul road condition reports as a score to depict the various state of haul road smoothness or roughness.

1.8 Research Validation

This study hypothesises that cement stabilisation is an economically viable method to construct mining haul roads at Lumwana Mine. The study hypothesis will be tested by analysing authorised data from Lumwana Mine and Resolution Systems to determine haul road construction and maintenance costs incurred versus the realised benefits of an approximately 300 meters ramp built using the Portland cement stabilisation method for the period under consideration.

1.9 Contribution to Knowledge

This research will add to knowledge on the financial and technical considerations required in determining whether a mine should build its haul roads using Portland cement stabilisation. In addition, the method will be highlighted as a guide and valuable tool in constructing cost effective and robust haul road networks capable of sustaining high volumes of material movements using ultra class haul trucks. This study will also be useful reference material for students, researchers, the industry, and other individuals and organisations that need to analyse the cost of constructing mine haul roads using Portland cement stabilisation in the mining industry.

1.10 Structure of the Research Report

This research report consists of five chapters. Chapter 1 is the introduction and covers the background of the research topic, the problem statement, the justification for the research, and the research objectives. The research methodologies applied in this study and the sources of the information are thereafter introduced. Finally, the research validation criteria, as well as the contribution to knowledge, are discussed.

Chapter 2 is the literature review and explains the significance of haul roads to mining operations and their financial effects being a resource that has to be managed. The effects of haul roads on fuel consumption and truck cycle times and how they influence mining costs are discussed. The study further examines haul roads geometry, pavement layers and material composition. The chapter finally explains a Caterpillar system used to monitor haul road condition severity connected to haul truck onboard pressure sensors.

Chapter 3 is the methodology chapter and discusses a ramp section at Lumwana Mine built using cement stabilisation. The performance and condition of this ramp are observed, and MaxMine system data was used to determine gains made in fuel consumption, truck speed, payload, entry speed, throttle positions and running surface smoothness.

Chapter 4 details the data obtained and provides an analysis of this data. Comparison of truck speed, payload, and fuel consumption are made before and after the application of Portland cement stabilisation. The Comparison led to understanding the value gains made on fuel usage, truck speed, cycle times, and maintenance hours. Research conclusions and, ultimately, recommendations are made in Chapter 5.

2 LITERATURE REVIEW

2.1 Chapter Introduction

This chapter reviews relevant literature that concerns the economics of mine haul roads. First, it sets the tone of the research by looking at relevant literature on the subject matter. Then, it outlines the impact mine haul roads make on key economic metrics that drive mining outputs, such as fuel consumption, truck cycle time, equipment maintenance costs and mine productivity. The chapter further outlines attributes of mine haul roads and how they influence mining costs. The use of technology to monitor some of these productivity metrics is also discussed.

2.2 Significance of Mine Haul Road Systems

Mine haul road networks are a significant aspect of mine production as they provide the access through which haulage of ore and waste material is made possible. Research has shown that truck haulage costs can account for up to 50% of total mining operating costs in open-pit operations (Thompson & Visser, 2003). Incurred savings due to improved road design, construction, and management directly impact the unit cost per tonne of material moved (Thompson & Visser, 2003). It is therefore noted that resources spent on haul road construction and maintenance are resources well spent as the resulting effect has a significant impact on the mine cost and production (Holman, 2006).

The urge to maximise production and keep mining unit costs low has exploited the principle of economies of scale toward moving more tonnes. Therefore, the past 30 years have seen the development of haul trucks that can carry up to 350 tonnes in one load from less than half that capacity previously. The improvement of roads that carry such equipment has unfortunately not developed at the same rate (Kaufman & Ault, 1977).

2.3 Cost Elements of Mine Haul Roads

The construction of mine haul roads affect how mine resources, which ultimately are broken down into cost elements, are involved in making mine haul roads optimised to deliver value. Such resources include mining heavy mobile equipment, road-building materials, and time. A mine haul road network built is expected to deliver value in how it helps the mine utilise scarce resources such as fuel, tyres, equipment hours, cycle time, and mobile equipment.

2.3.1 Fuel usage

Fuel is one scarce resource consumed in larger quantities in an open-pit operation. As mine operations endeavour to be efficient, productive, and cost-effective, fuel consumption is one element in the mine cost equation that cannot be ignored. Diesel is one such fuel commonly used in heavy mobile equipment on mine sites. In the United States of America (USA), diesel accounts for about 34% of the fuel needs of its mining industry (U.S Energy Information Administration, 2022). Figure 2-1 depicts the distribution of energy consumption in USA.

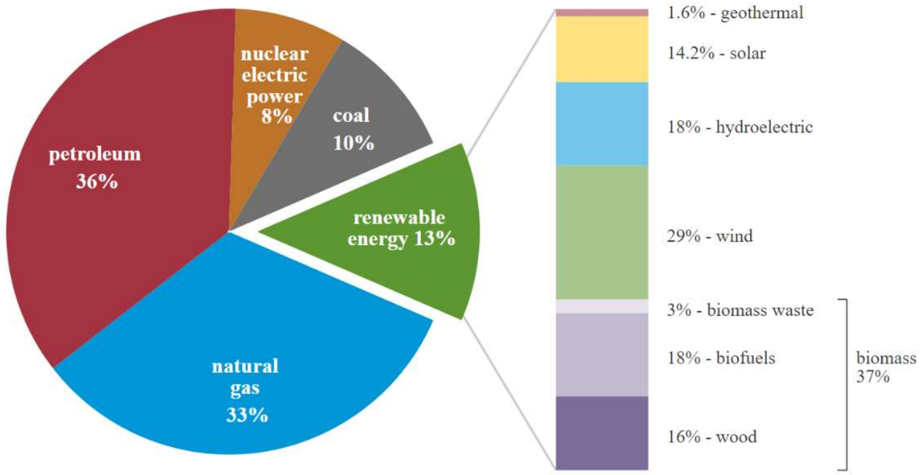


Figure 2-1. U.S.A primary energy consumption by energy source (U.S Energy Information Administration, 2022)

Sahoo et al. (2014) were further able to conclude that the principal means of transporting ROM material from open-pit operations to crushers and waste dumps is through mine haul (dump) trucks. In a typical coal mine in India with an installed capacity of 2.5 Mt/year, the fuel consumption of these trucks accounts for about 32.5% of the energy usage. Figure 2-2 depicts the energy distribution of a typical coal mine operation in India

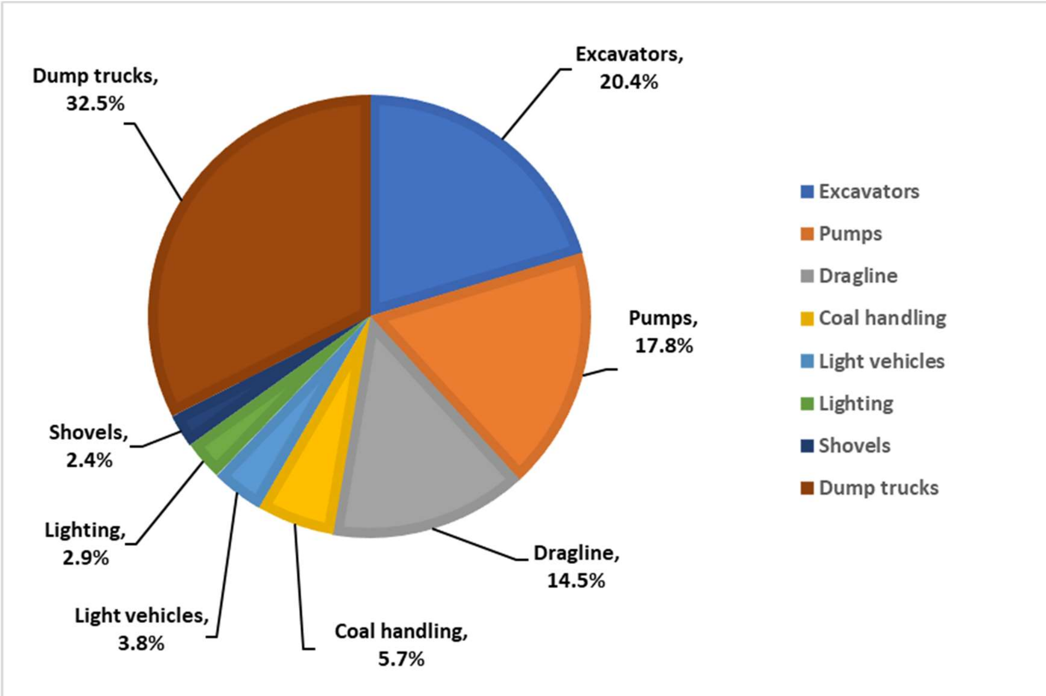


Figure 2-2. Energy usage pattern of typical open-cast coal mine in India (Sahoo, et al., 2014)

Consequently, the amount of fuel resources allocated toward hauling ROM material to various destinations in a mining operation is significant. Thompson and Visser (2003) deduced that truck haulage costs, of which fuel is the main component, can account for up to half of the total operating expenses of a mining operation. Therefore, efficient fuel consumption in this sector of the mining operation is an area of research that has received attention from different aspects of the industry as any savings directly impact mine operating costs and accrue environmental benefits in terms of reduced pollution emissions.

Bajany, et al. (2019) developed a model that optimises the route trucks take to the loading units while keeping fuel consumption to a minimum and meeting the needs of the dumping site in each truck and shovel cycle. The model is suitable for all open-pit mine operations, including truck-constrained operations. Furthermore, the setup took into consideration all the idle time of shovels and waiting time at the dumping and loading units of the haul trucks. This study also demonstrated effectiveness in determining the best shovel allocation in the case of a heterogeneous shovel fleet.

Rodovalho et al. (2016) created a method of analysis of fuel consumption variables in mining haul trucks used in large iron ore mines that are said to have the potential to improve fuel usage by as much as 10%. The model identifies and ranks these variables according to their priorities from data obtained using actual data sets. It used average speeds of haul trucks incorporated into multiple linear regression functions as mathematical modelling and statistical analysis tools.

Soofastaei et al. (2016) developed a model for surface mine operations that, based on artificial intelligence, aims to reduce fuel consumption in haul trucks. The study examined the effect of load, total haul road resistance, and truck speed as major parameters in haul truck fuel consumption. It then uses the genetic algorithm (GA) and the artificial neural network (ANN) to develop a model that estimates and reduces fuel consumption. This model was applied and tested on datasets that were collected from large surface mine operations in Australia and the USA on equipment models such as the CAT 793D, CAT 775G, and CAT 777D. The developed model, through its ANN and GA functions, can provide optimum truck payload, haul road resistance, and truck speed values that reduce haul truck fuel consumption.

2.3.2 Truck cycle time and its impact on truck maintenance costs

Truck cycle time is a key and essential metric to optimise a mining operation's productivity. Fishonga and Mutambo (2017) defined cycle time as the total time taken by a dump truck to make a complete cycle. This time includes time taken to haul, manoeuvre at the dump including dumping time, return manoeuvre at the loading unit including loading time, and all the queuing time incurred while waiting to load.

Improvements in cycle time have an immediate and direct impact on mine operations' productivity. In a study undertaken at Ruashi Mining in The Democratic Republic of Congo, Nday and Thomas (2019) were able to identify the constraints that had a negative impact on the cycle time, which in turn impacted the mine's productivity. Mine haul road conditions were among the four restrictions to a productive cycle identified in the study. Optimising the cycle time for this operation by working on the identified constraints, such as mine haul road conditions, could improve the cycle time by as much as 13.2% on the B50D articulated dump truck (ADT) and 8% on the B40D ADT. The study recommended improvement in the mine haul road and equipment maintenance if such a reduction in the cycle time were to be achieved. This would have a significant positive impact on the mine's production, which had lagged significantly. At the time of the study, the mine had only achieved its production target for only four months out of the 12.

In a study to determine possible productivity improvement options for the Mamatwan Manganese Mine in South Africa, Mkhatshwa, (2009), was able to deduce that the productivity of the mine could be improved if the rolling resistance was reduced to 2%. Furthermore, by utilising the mine's maintenance equipment to smoothen out haul road surfaces, the cycle time of the CAT777 haulage trucks could be reduced by 15%, thereby increasing the mine's output in production by 18%.

Maintenance costs form a significant part of mining cost drivers. For example, at Harmony Gold's Hidden Valley mine in Papua New Guinea, maintenance costs of haul trucks, and their tyres form about 51% of the operation's mining costs (Harmony Gold, 2008). Figure 2-3 shows a graphic representation of the mining cost drivers at Harmony

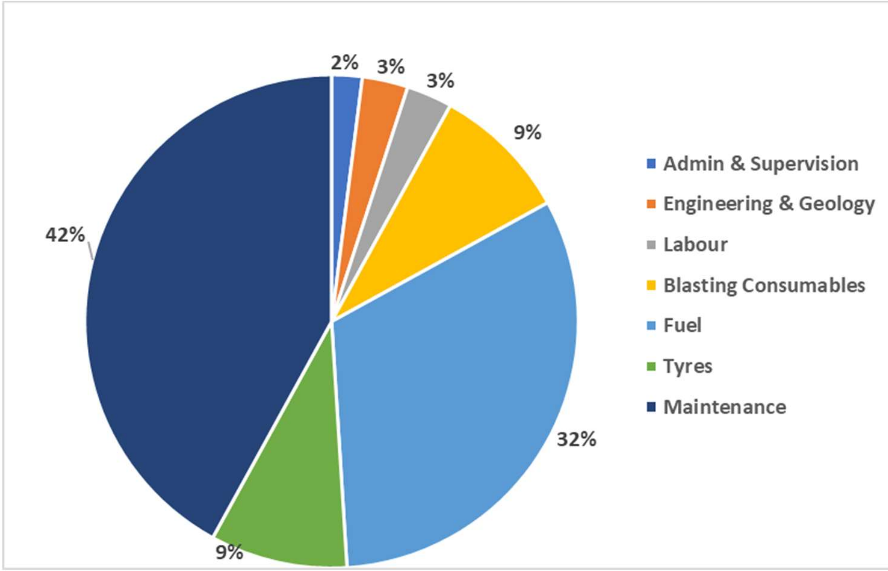


Figure 2-3. Mining cost drivers at Harmony (Harmony Gold, 2008)

Mining operations will therefore, undertake robust maintenance plans on their plant and equipment to minimise the impacts of unscheduled downtime on equipment which can be in form of lost production or direct maintenance costs (Robatto, et al., 2023).

The cost associated with maintenance is attributed to the stringent maintenance regimes carried out by mining operations. Mining organisations run planned component replacement (PCR) programs which form the core of their maintenance and repair systems. Such PCR programs are scheduled based on the life cycle of the components which is a function of the equipment running hours (Galatiya, 2021).

Mine haul truck components also undergo scheduled changeouts as and when they are due. The cost of carrying out these component changeouts is only of value to the mining operation if the truck moved ROM material more or equal to its productivity during the period it accumulated these hours. Such a scenario is only possible if the haul truck meets its production cycle efficiently. Cycle time, which is also influenced by the haul road condition, directly affects the maintenance cost. Thus, increased speed and reduction in travel time will be observed as well as how it provides gains in maintenance hours.

2.4 Haul Road Geometry and Design

This section will briefly discuss the haul road alignment, geometry, and design. The full technical detail of these topics is outside the scope of this study.

2.4.1 Haul road geometry

The geometry of any haul road network must be suited to the requirements of the mine. However, getting the best fit haul road geometry is often challenging because an ideal haul road with the best vertical gradients and horizontal curvature parameters will conflict with the mine pit design requirements. The underlying principle is, therefore, one that allows for haul road design that considers horizontal curves large enough to enable the travel of haul trucks at the maximum speed and a vertical gradient that allows smooth travel without discontinuities (Visser, 2015).

Any mine haul road system must be designed to accommodate the largest haul truck on the mine. This will range between 2.5 to 3 times the size of the largest truck on the mine. The grade up the ramp does not usually exceed 10%, with most mines keeping 8% as the optimum (Tannant & Regensburg, 2001). Figure 2-4 shows the gradient comparison for a uniform and non-uniform grade.

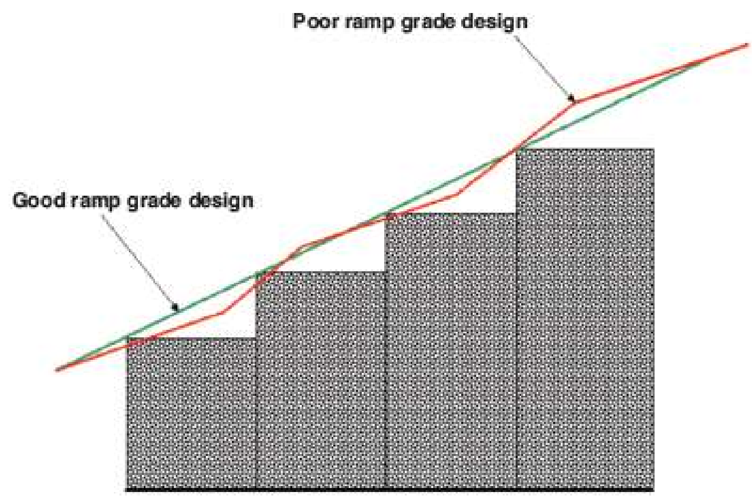


Figure 2-4. Uniform (correct) and non-uniform (incorrect) gradient (Visser, 2015).

The ideal ramp system with a constant ramp system supports good truck productivity. In his study of how haul roads can make money, Visser (2015) deduced that removing gradient breaks on a haul road ramp and running a constant grade increased truck productivity by 38%. He demonstrated that a ramp varying from 8% to 13% grade would only support a fleet of seven trucks with 340 tonnes of material per truck-hour (this equals to 2380 tph). Removing the gradient breaks and implementing a 10.3% constant grade would accommodate 470 tonnes of material per truck-hour. That is, using an improved haul road design and construction guideline would achieve the same target using five trucks instead of seven trucks as the truck cycle time will be reduced and truck capacity has increased. In addition road maintenance will be kept to the minimum as the trucks will not damage the road due to wheel spinning as a result of gear changes.

The maximum superelevation on curves and switchbacks on haul roads does not exceed 4% in most mines, with the cross fall kept to an optimal value of 2% to 3%. Part of the road geometry includes the consideration for safety berms on the open edge side of the haul road, which are kept at more than half the diameter of the tyre on the biggest haul truck, and the safety berm height would therefore range from 1.2 meters to 2.5 meters (Tannant & Regensburg, 2001).

Mine haul road alignment design is a function of the mine planning primarily the medium-term mine planning. This is because the alignment of any haul road has to tie in with a mine plan so that it does not cause unnecessary waste stripping. A common challenge is that there is usually insufficient room to allow high-radius curves. However, the design must be done considering the turning radius of the biggest dump truck (Visser, 2015).

2.5 Haul Road Pavement Design

Mine haul road pavement design outlines the process of developing the most economical combination of pavement layers, concerning both thickness and the type of materials available, that is proportionate with the in-situ material and haul traffic to be carried over the design life of the road (Thompson & Visser, 1999). Such pavement layers include the subgrade, sub-base, base, and wearing course, as outlined in Figure 2-5

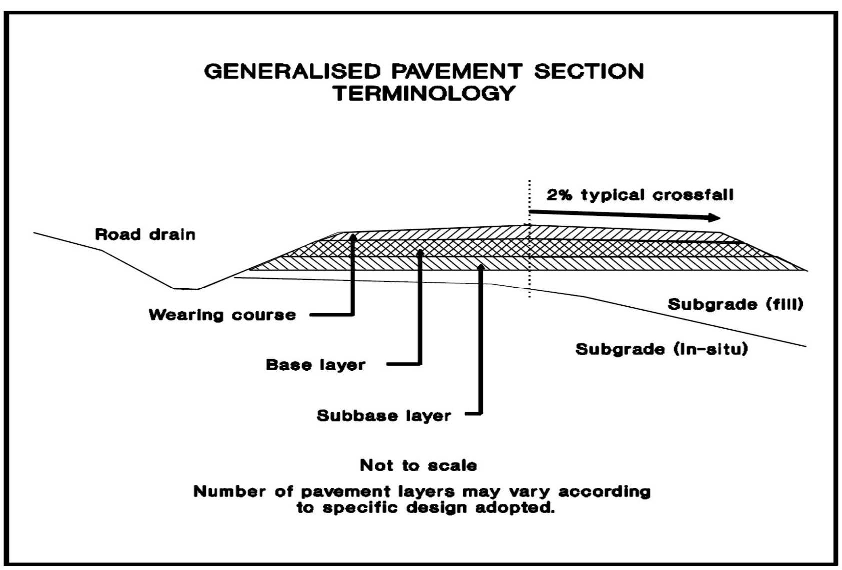


Figure 2-5. Generalised haul road section terminology (Thompson & Visser, 1999).

Mine haul road pavement design is critical in achieving a durable and productive haul road. One of the most important fundamentals of a road design is a robust haul road base. The base must be built of material with adequate load bearing capacity enough to support the weight of the intended traffic and prevent sinking, rutting and overall deterioration of the haul road. The load bearing capacity of road building materials is a determined through detailed procedures by qualified soils engineers.

According to Thompson and Visser, (1999), the mechanistic structural design technique and the CBR method are some of the techniques used in arriving at the constitute layer thickness that has proven to be effective in mine-haul road pavement design. The CBR method uses a pattern of curves plotted on a chart from road building material samples that have undergone laboratory tests to determine their properties. The chart will deduce the sub-base or base thicknesses after interpreting vehicle wheel load specifications for the haul road trucks and obtained CBR test values. The thicknesses of the various layers are thereafter determined using this method.

2.6 Haul Road Construction Materials

It is common practice in most mining operations to source road construction materials from the ROM waste that comes from the pits. Such material makes constructing haul roads cheaper as all associated costs of blasting, loading and hauling are absorbed in the mining operations costs. In instances where the materials may not be strong enough for constructing durable haul roads, mine operations will usually decide to use the materials in the lower layers as subgrade or sub-base material and import the materials for the base and running surface from nearby competent borrow pit sources. After analysing the layer material properties, the decision on which road material to use for each layer is determined. Available materials can be combined with the hardest materials on top, while the layers below are placed in a succession sequence that follows their compressive strength. Such a combination results in the least vertical strain on the road layers (Kaufman & Ault, 1977). Thus, material selection guidelines must take cognisance of road-user functional performance requirements and the limitations imposed by material availability, cost, and volume considerations (Paige-Green, 1989).

2.6.1 Material stabilisation

Kaufman and Ault (1977), defines stabilised earth to be the earth that, through additives or special procedure, has been transformed from a natural unconsolidated state to a degree of stability that will accommodate heavy vehicles. This is done by incorporating soil binders such as cement, lime, calcium chloride, asphalt or lignosulfonates.

Stabilisation is used to overcome deficiencies in available road construction materials by enhancing the material properties for pavement design purposes. This technique has been in use in South Africa since the 1940s, with the method being well-established on many highway projects in South Africa (Fossberg & Gregg, 1963).

Fossberg and Gregg, (1963), further classifies this technique into three categories;

I. **Cement and lime stabilisation**. This aspect of stabilisation includes additives such as slag, fly-ash and Portland cement;
II. **Bituminous stabilisation**. This type of stabilisation includes the use of tar, bitumen, and other products of the petroleum industry; and
III. **Chemical and other stabilisation**. This category includes other additives not covered by the above two categories.

Bhattacharja and Bhatty (2003) performed a study to understand the effectiveness of Portland cement and hydrated lime stabilisation in improving the engineering properties of various soil types. They compared three soil types whose plasticity index (PI) values ranged from 25 to 42 under testing conditions that were kept as similar as possible. The study concluded that the Portland cement and hydrated lime were effective stabilisers for moderate to high plasticity soil types. However, Portland cement performed better than hydrated lime at lower dosages, as low as 3%, and even better at double the dosage.

The uniaxial compressive strength (UCS) of moderately PI soil stabilised with cement was consistently higher than the lime-stabilised soil. In addition, the load-bearing capacity of the cement-stabilised soils was superior to the lime stabilised based on the CBR results obtained in the study. The study further concluded that good results are obtained with cement stabilisation if compaction is done immediately after mixing (Bhattacharja & Bhatty, 2003).

Behera (2016), undertook a study that looked at a mix of fly ash and overburden stabilised with lime in various proportions to determine their suitability in mine haul road construction. This study was motivated by the fact that fly ash, as a by-product of thermal coal plants, occurs in abundance and overburden stripping is part of the mining process. Both fly ash and overburden material could be of great use if the right proportion of each is found which sustains the construction of mine haul roads.

The study by Behera (2016) concluded that fly ash and mine overburden in various proportions without additives do not produce a strong enough mixture of for the base layer for mine haul road construction. With the addition of limestone as an additive, the UCS and CBR values of the mixture increased. It was observed that the CBR values increased from 22% to 77%, while the UCS values increased from 0.71 MPa to 2.5 MPa. The study further concluded that the best mix proportion of fly ash to the overburden was 30:70. The best results are obtained by premixing the overburden with 9% lime before applying the fly ash.

Stabilisation products such as those highlighted above basically enhance the strength of various road-making materials by working on the properties such as reducing the plasticity index, increasing the shrinkage limit, and meeting strength value limits such as the CBR, UCS, and resilient modulus (Lafarge, 2012).

2.7 Haul Road Rolling Resistance

Rolling resistance is defined as the amount of force needed to overcome the retarding effect between tyres and a road surface. A rolling resistance coefficient, determined by dividing the rolling resistance by the normal force on a truck tyre commonly represents this rolling resistance. (Soofastaei, et al., 2016). Rolling resistance is further defined as the energy loss per distance travelled by a vehicle due to non-elastic deformations of the tires and failures in the wheel suspension system (Andersen, et al., 2015).

2.7.1 Parameters that Influence Rolling Resistance

(Soofastaei, et al., 2016) conducted a survey to determine parameters that influence rolling resistance in mining haul roads. A score between 0 and 100 to depict the influence on rolling resistance was assigned to each parameter where 0 is the least influential while 100 is highly influential. Of the 15 parameters surveyed, Road Maintenance, Tyre pressure, and Truck speed were the most influential parameters scoring between 80 and 90. The survey deduced a relationship between road maintenance interval and rolling resistance such that an increased road maintenance interval resulted in increased rolling resistance. Increasing tyre pressure within the tyre design specification was however observed to cause the rolling resistance to reduce. Increasing the truck speed was found to have a corresponding increase in rolling resistance coefficient and consequently rolling resistance for both rough and smooth road surfaces. The factors that influence truck speed such as payload, road conditions, driver behaviour, grade of the haul road, and tyre condition were taken into consideration in arriving at such a conclusion. It was however noted that lowing the truck speed is desirable only if the only factor being considered is rolling resistance. In mining haul truck speed optimisation, cycle times, safety and productivity requirements are given consideration to ensure full hauling operation efficiency is achieved.

2.7.2 Rolling Resistance Measuring Techniques

(Andersen, et al., 2015) undertook a study on rolling resistance which focused on surface and texture modelling, measuring techniques, tyre models and macro-modelling of rolling resistance. They classified rolling resistance into the following measuring techniques;

- Trailer methods;
- Coast-down methods;
- Fuel consumption methods; and
- Drum tests of tires.

The trailer method: Force transducers connected to a trailer's test wheels are used to measure rolling resistance. The trailer is towed by a vehicle allowing for one or more of it's test wheels to collect the data to the force transducers

The coast-down method: Operates more on the technique of driving resistance than rolling resistance. The coast-down method is done on the principle of accelerating the vehicle to a certain speed and letting it roll freely in a clutch down or neutral gear position. During the period the car coasts down, velocity and time are measured. The data collected includes other parameters such as wind speed and road texture. All collected data must be fitted to mathematical models for further analysis in order to come up with the rolling resistance.

The Fuel Consumption Methods; Are a generic way of assessing the rolling resistance as they include all possible factors that influence rolling resistance. Many factors influence energy losses experienced by a vehicle with rolling resistance among them making it difficult to solely isolate the energy losses to any one factor. Fuel modelling therefore involves a lot of complex systems bringing together a lot of components such as the powertrain, driver and brake control, the wheels, the engine submodels, the road, and the meteorological conditions.

Drum Tests of Tyres: This is a method of measuring rolling resistance by the drum test such that a test tyre is held up against a drum and a load is applied on the tyre. The rolling resistance is deduced by rotating the drum and measuring the resistance the tyre exerts on the rotation of the drum. This method offers an advantage as it excludes all other factors that influence the tyre rolling resistance.

Another theoretical means of calculating rolling resistance applicable to general situations was reviewed and presented below. The Engineering toolbox presented a theoretical calculation that requires knowledge of the rolling resistance coefficient as in equation 3.8. calculating the rolling resistance coefficient is further done using equation 3.9 .

The rolling resistance (Fr) of the haul road is calculated using the equation:

$$Fr=cW \qquad \text{Equation 3 8.}$$

Where: c is the rolling resistance coefficient W is the normal force of the truck. W will be expressed by the mass of the truck multiplied by acceleration due to gravity ,g. (The Engineering ToolBox, 2008)

The rolling resistant coefficient (C) is further given by:

$$C=V2/2xgxS \qquad \text{Equation 3 9.}$$

Where: V is the speed of the truck at the start of coast-down (m/s), g is the acceleration due to gravity (m/s2) and S id the coast down distance in meters (m). (Palasz, et al., 2019).

2.7.3 Measuring Rolling Resistance in Mining Haulroads

Rolling resistance worked out in techniques above is proportional to speed and is influenced greatly by air drag. In mining, the speeds are too low for air drag to have an effect on the size of trucks in use. The haul road condition in mining plays a significant role in due to the mass of the equipment and the payload. Rolling resistance is mainly impacted by tyre penetration in the haul road surface and flexing of the tyre under heavy load.

(Thompson, 2017) outlined a qualitative method estimating rolling resistance from visual evaluation. The method is based on road defect classification system where key defects influencing rolling resistance are identified. A product of defect degree and extent are scored in a table with each of these parameters measured on a scale of 1-5. The sum of the of the individual defects rated is converted using a scoring sheet to give a rolling resistance for the section of haul road under consideration. This evaluation method is based on a visual assessment of a defect “extent” (i.e how much) and “degree” (i.e how bad) of the road is affected. Where the defect is not evident on the haul road, a score of 1 is scored for both the defect degree and extent. The defects considered to have the most influence on mine haul road rolling resistance are;

- Potholes
- Corrugations
- Rutting
- Loose material; and
- Stoniness- fixed (in wearing course)

The final score is called the roughness defect score (RDS) which is obtained through a simplified table in table 2-1

Table 2-1 Roughness defect evaluation score sheet (Thompson, 2017)

MINE HAUL ROAD ROLLING RESISTANCE VISUAL EVALUATION				
DATE			EVALUATOR	
ROAD			VEHICLE SPEED km/hr(V)	
CHAINAGE			TRAFFIC kt/day	
DEFECT	**RDS (Rolling resistance)**			
	DEGREE (1-5)		**EXTENT (1-5)**	**DEFECT SCORE**
Potholes		x		=
Corrugations		x		=
Rutting		x		=
Loose Material		x		=
Stoniness- Fixed		x		=
TOTAL ROUGHNESS SCORE (RDS)				
ESTIMATED ROLLING RESISTANCE (%) Refer to graph for rolling resistance percentages				

The RDS score in table 2-1 is converted to rolling resistance (%) using the graphic representation in figure 2-6 at a specified truck speed.

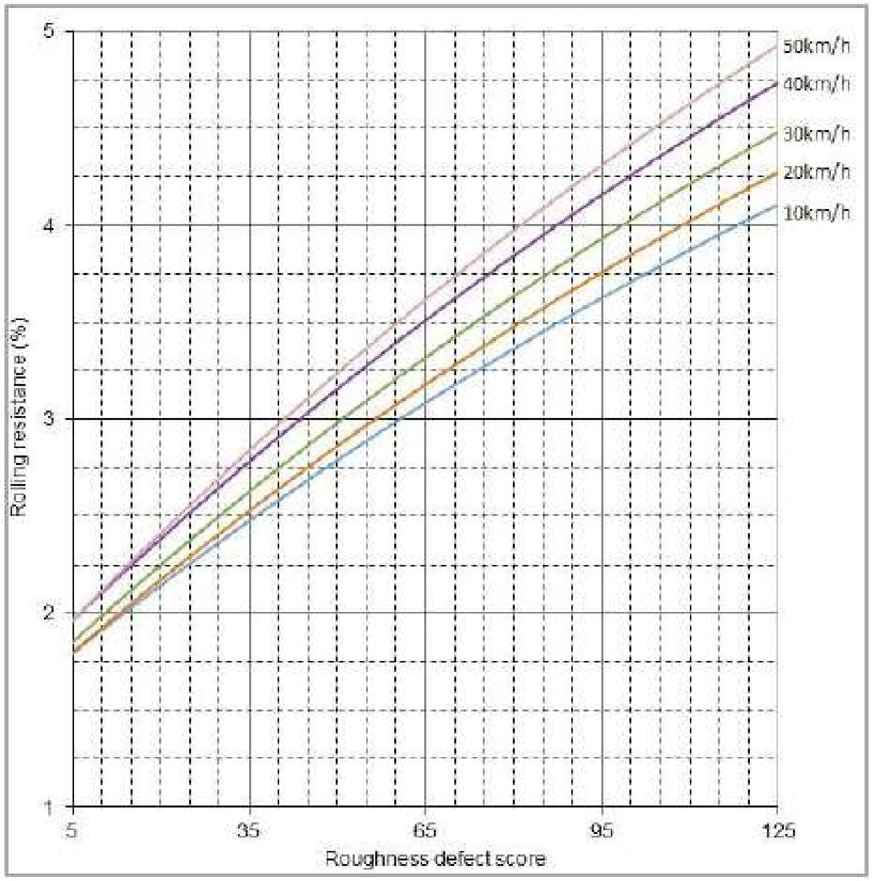


Figure 2-6 Rolling resistance estimation chart

2.8 The MaxMine System

MaxMine is an independent fleet monitoring system installed on the mine haulage trucks. The system owned, by Resolution Systems (Pty) Ltd. can monitor operational productivity through sensors installed on the haul trucks.

MaxMine is a data analytics system used to optimise the mining mobile equipment fleet. It is a mobile fleet management and optimisation system that enables mine operations to utilise its mobile fleet efficiently by harnessing the available improvement opportunities (Resolution Systems, 2020).The MaxMine system is divided into two major components. The hardware and software components. A high-level summary of each is outlined below.

2.8.1 MaxMine hardware module

The MaxMine hardware module on the mine mobile equipment includes a data logging unit and a GPS antenna mounted on the front handrail. The system can sometimes use the existing fleet management system antennae where possible. Figure 2-6 shows a truck's data logger and GPS antennae schematic configuration.

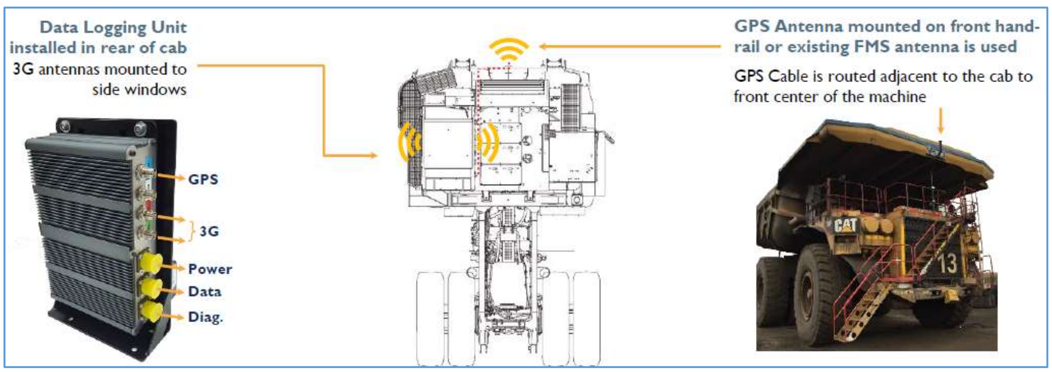


Figure 2-7. MaxMine hardware installations on a haul truck (Resolution Systems, 2020).

The above-installed MaxMine hardware interfaces with equipment onboard the data bus and collects data used in further analysis in the software systems hosted in the cloud. The hardware installation on any equipment is done within two to three hours per equipment, usually while the machine is undergoing planned maintenance. The MaxMine hardware expertise works out the bracket and logger mounting positions in collaboration with the mine engineering department, which must agree to the design and modification before the fabrication is done. This collaboration ensures that the installation of MaxMine hardware does not interfere with the normal functions of the mining equipment (Resolution Systems, 2020).

2.8.2 MaxMine software module

The MaxMine software configuration is set up into two segments. These are the in-field and the cloud/user interface software modules. Figure 2-7 shows these two segments in perspective MaxMine (2022).

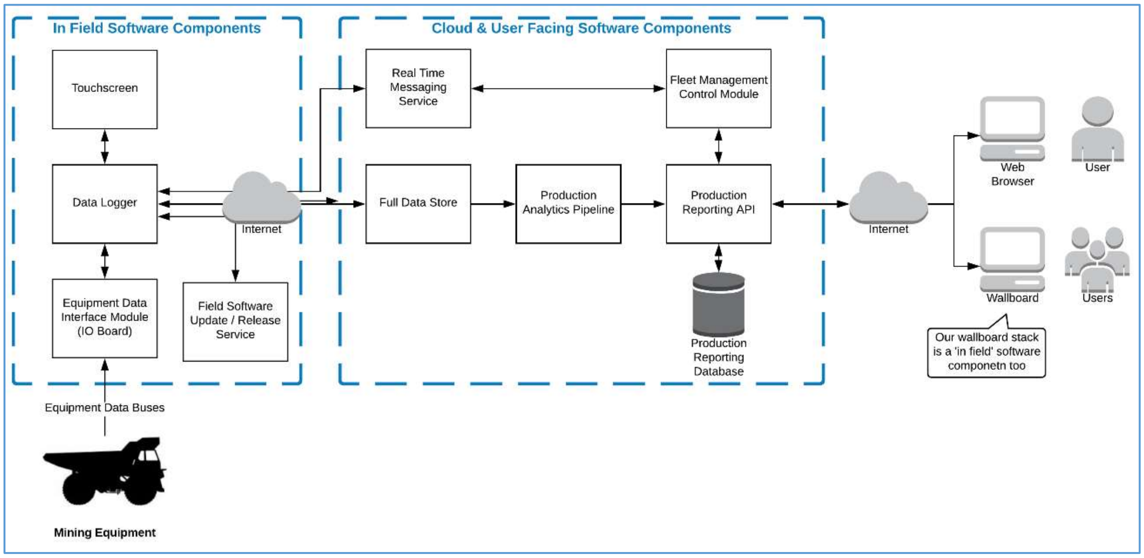


Figure 2-8. MaxMine software modules (Resolution Systems a, 2022).

MaxMine works by collecting enormous amounts of raw, high-rate data at frequency ranges of between 10 to 50 Hz from multiple data buses on mine equipment. This data is routed through the MaxMine system, which applies advanced algorithms to create passive feedback and production metrics classification (Resolution Systems b, 2022).

2.8.3 Payload calculation in MaxMine

Payload calculation is one of the functionalities of the MaxMine system. The payload report is based on information from two sources, namely the payload management system (PLM) installed on the truck by the original equipment manufacturer (OEM) and the MaxMine payload calculated from the truck strut pressures as the machines get loaded (Resolution Systems a, 2022) . The PLM system is programmed to transmit payload information over the onboard busses. MaxMine connects to the equipment busses to access this payload information and records it to the data logging unit outlined in Figure 3-2. The MaxMine software independently interpedently calculates the payload using the changes in strut pressures as the shovels load the trucks. The payload is calculated under any condition, while the PLM systems depend on the haul truck being on a level surface or the measurement being re-taken once the haul truck gets into second gear.

Discrepancies between the MaxMine software and the PLM payloads do occur mainly because of calibration issues with the onboard PLM system, which relies on suspension cylinders for calibration. The MaxMine software payload is calculated throughout the entire haul, not just at a single point when it gets into the second gear. The return empty is used to calibrate the sensors, reducing the need to carry out manual calibration. The MaxMine algorithm, when calculating haul truck payload, uses raw strut pressure data, payload offset, truck geometry, and road camber parameters. Figure 2-8 shows the pressure intensity during a complete cycle.

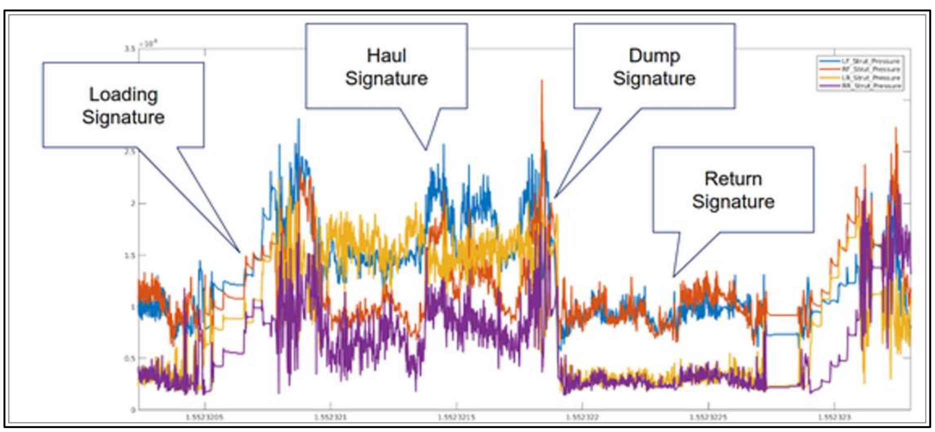


Figure 2-9. Truck strut pressure intensity during a cycle (Resolution Systems a, 2022).

The X-axis shows the distance travelled while the Y-axis shows the amplitude of the strut pressure which shows continuous monitoring of the payload. The various colours represent the four struts of a haul truck- two in front and two at the rear. The haul signature strut pressure shows the strut pressure for the period a loaded truck moves from the loading unit to the dump. MaxMine uses the whole duration of this period to evaluate payload, which creates less impact from noise (Resolution Systems b, 2022).

The return signature strut pressure shows the pressure status for the period an empty truck returns from the dump to the loading unit. MaxMine uses this period to calibrate the truck payload by updating the estimate of the truck's empty weight (Resolution Systems b, 2022)

2.8.4 How MaxMine calculates haul road condition

This section outlines the haul road condition calculation (HRC) calculation. The feature is handy in identifying areas of haul roads that are roughest using a mine heatmap (see Figure 3-5). The algorithm uses haul truck strut pressure, GPS position data, and truck data sources to determine the road roughness index (Resolution Systems a, 2022). For the algorithm to calculate a haul road condition, the following must be satisfied:

- The haul truck must be in motion;
- The haul truck must be performing a haul and return or a haul plus activities such as out-of-cycle refueling maneuvers; and
- The haul truck must be within the bounds of the mine site.

2.8.5 How MaxMine calculates fuel usage on a machine

This section summarises how MaxMine works out the fuel consumption. Fuel usage is determined from an aggregation of fuel rate data throughout the duration of the truck operating activity. The system connects to the data logic unit of the equipment data busses and decodes the fuel usage from the truck fuel system. System data on how many times and to what extent the injector nozzles have opened up to inject fuel into the engine cyclinders is decoded and aggregated to come up with fuel used at an instantenous moment. Figure 2-9 provides a summarised flow chart of the process that MaxMine uses to calculate haul truck fuel (Resolution Systems a, 2022). The algorithms on how MaxMine decodes the fuel used by the haul trucks are proprietary and not for publication even though the results are being used with permision from Lumwana mine and MaxMine.

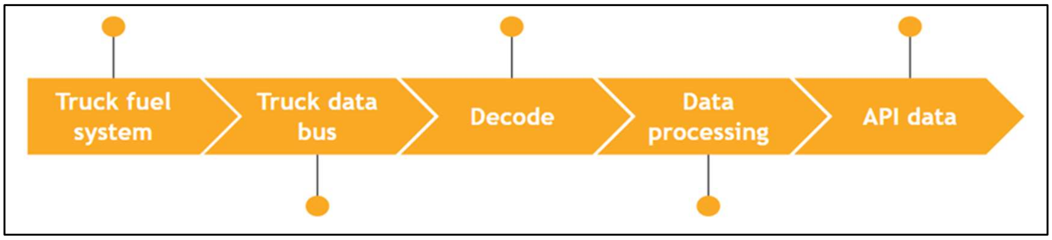


Figure 2-10. MaxMine fuel calculation process (Resolution Systems a, 2022).

2.8.6 How MaxMine calculates Truck Speed

The truck speed is calculated in two ways. Firstly the MaxMine software claculates the truck speed through the onboard data bus connection using the data logic unit. The software uses the GPS and the onboard data to work out the speed. Secondly, MaxMine either installs its custom GPS antenna on the equipment or uses existing GPS antenna installations to get the GPS data, including position and speed.

The speed data gathered from the onboard systems is the speed from the truck's wheels. The GPS works out the speed, which it compares to the wheels' speed.

A similar software developed by Caterpillar is discussed in section 2.9.

2.9 Caterpillar Road Analysis Control (RAC) Technology

Holman (2006), discussed a system used in Caterpillar equipment for monitoring haul road condition severity. The system is called the road analysis control (RAC), and it uses a system of onboard pressure sensors to measure component loading and impact shock to identify problem areas on the haul road. The RAC system collects strut pressure data from each wheel at a rate of ten times a second and then computes the difference in the strut pressure between wheels, thereby determining the front and rear axle wheel strut pressures known as the pitch. RAC further determines the diagonal wheel strut pressures known as the rack and the side-to-side strut pressures known as the bias. The RAC system, therefore, correlates pitch and rack by comparing them to predetermined design tolerances within acceptable limits. Figures 2-10 to 2-12 illustrate the pitch, rack, and bias.

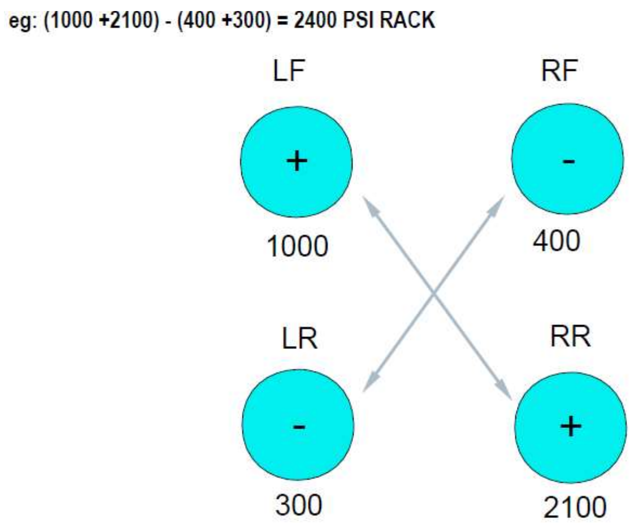


Figure 2-11. The rack (LF+RR)-(RF+LR) (Holman, 2006).

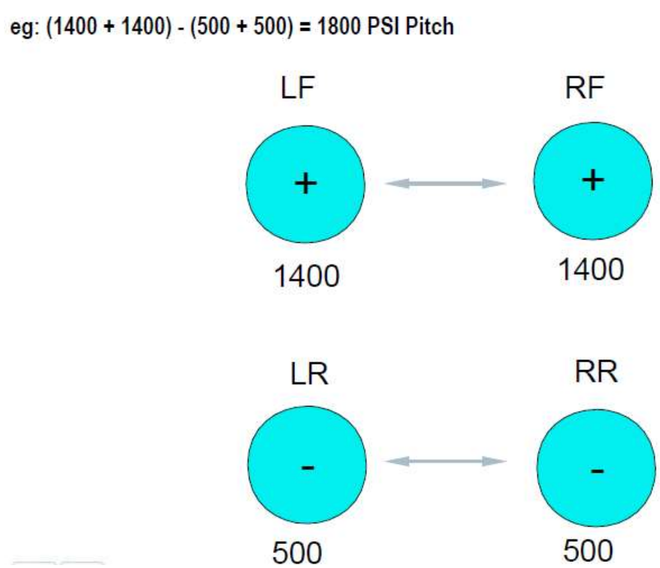


Figure 2-12.The pitch (LF+RF)-(LR+RR) (Holman, 2006)

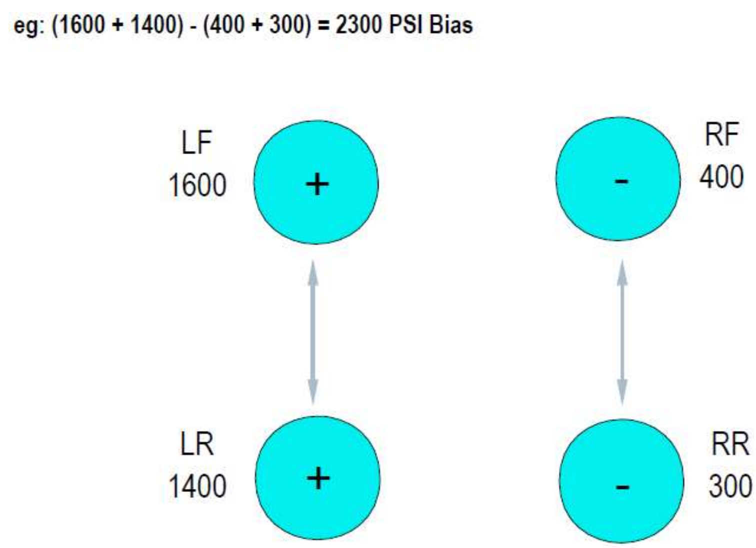


Figure 2-13. The bias (LF+LR)-(RF+RR) (Holman, 2006)

The system can transmit real-time global positioning system (GPS) location and data to the maintenance crews through a radio signal where such equipment is available. It can also establish a relative severity of each hauling cycle through a fatigue equivalent load analysis (FELA) index, which develops in the process.

2.10 Chapter Summary

Every mine operation sets within its objectives to mine productively and efficiently. To achieve this objective, critical productivity and efficiency drivers are identified and adequately resourced to ensure they impact mining operations positively. Mine haul roads are essential in ensuring that mining operations mine productively and efficiently.

Given the importance of mine haul roads, as discussed in Section 2.2, their impact on fuel consumption and use was discussed in Section 2.4.1. Various scholars addressed the topic from different perspectives, focusing mainly on the mine haul truck parameters, fuel systems and the mechanism in which they are operated. The effect of a good haul road network on mine haul truck cycle times was also discussed. Parameters on haul road geometrics and their pavement layers were also addressed, with studies on various stabilising additives such as fly ash and lime. Summary notes about the MaxMine system was discussed and the various parameters that it measures whilst a haul truck is in operation were covered. Finally, a Caterpillar-based haul road severity condition monitoring system that uses onboard pressure sensors to identify problem areas was highlighted.

The need for continuous improvement in mine haul roads is therefore key to ensure that this important infrastructure is kept fit for purpose in supporting mine production. In the next chapter, methods that detail Portland cement stabilisation in building a robust mine haul road are discussed and techniques to measure the resulting production and financial gains are introduced.

3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter will highlight the methodology used in the study and the data obtained. The chapter will give input into the overall analysis of the research findings leading to the conclusions.

3.2 Research Methodology

The research evaluated the cost-benefit of constructing mine haul roads using cement stabilisation. The case study used in this research is Chimi West 5 (CW5) Ramp1 at Lumwana Mine. The cement stabilisation technique was used in the construction of a 661 m stretch of this ramp. A 300 m of this ramp provided a common overlap between the stabilised ramp and the old unstabilised section. Figure 3-1 shows the cement stabilised section and the common overlap area before cement stabilisation.

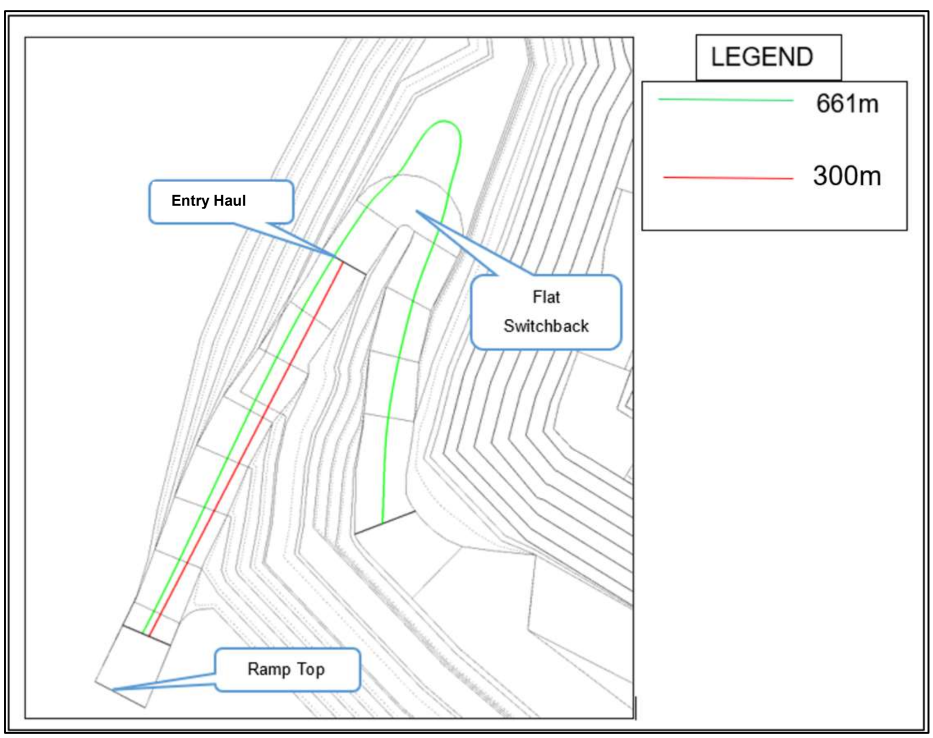


Figure 3-1. Section of CW5 Ramp1 investigated in the study (Barrick Lumwana Mine, 2020).

The stabilised haul road section was opened to heavy mobile equipment at the end of June 2020, with research data gathered up to December 2020. During the research period, heavy mobile haul trucks loaded with an average 250 tonnes net payload of material from the pit repeatedly used the road section. An average of 470 truckloads per day were hauled through the ramp section during the research period. During the research period, monitoring the haul road's condition was done using the MaxMine system. In addition, the study noted the frequency of haul road maintenance using motor graders and any other equipment together with any road maintenance materials.

During the research, road severity condition monitoring, which measures the surface smoothness of the haul roads, was achieved utilising sensors installed on truck struts, which gave MaxMine the ability to produce HRC reports every shift. The process involved measuring strut pressure as the haul truck drove on the mine haul roads. The strut pressure from the front two struts was converted into a force whose root mean square (RMS) of the high-frequency component was calculated per 10-meter interval. The RMS was then partially averaged with other trucks with the same load condition, either loaded or empty, for the same shift (Resolution Systems, 2021). Site-specific thresholds group the results into smooth, light, moderate, rough, and extremely rough, with each of these given a specific colour code as highlighted in Table 3-1.

Table 3-1. HRC thresholds for haul road condition monitoring (Resolution Systems, 2021)

	Haul Road Condition Metric	
	Minimum	Maximum
Smooth	0	18
Light	18	27
Moderate	27	42
Rough	42	66
ExtremelyRough	66	inf

Figure 3-2 shows a heat map of the haul road condition report. The below heatmap report is sent out as a daily report to a mailing list and helps the mine site focus most of its resources, such as graders and dozers, in the areas in red to purple that have the poorest score.

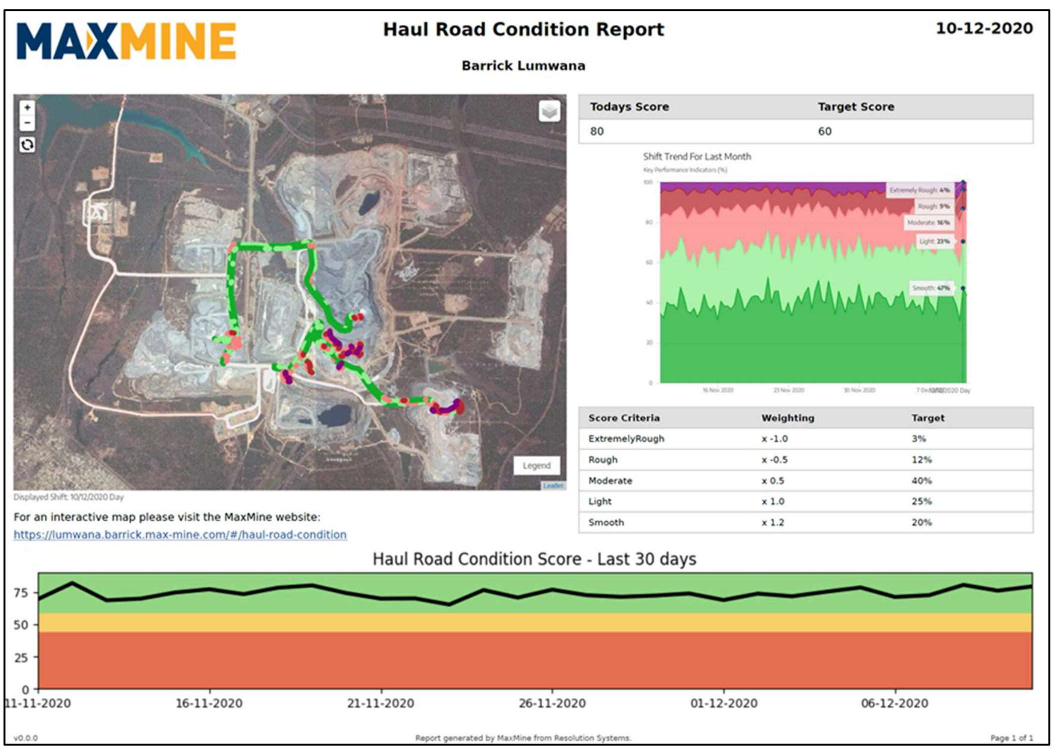


Figure 3-2. Heatmap from the haul road condition report (Lumwana Mine, 2020).

The MaxMine system installed on the haul trucks also recorded truck position, velocity, and other operational parameters, such as fuel and payload, every second of operation through the section under study. The research used the recorded data to work out the following quantities for every loaded and return trip through the common overlap section of the study:

- Entry time;
- Time through the section;
- Payload in tonnes;
- Average speed (km/h);
- Distance travelled (m);
- Height difference (m);
- Entry speed (km/h);
- Min speed (km/h);
- Entry throttle (%);
- Percent full throttle (fraction of haul where the throttle is > 97%); and
- Fuel used (L).

The study used MaxMine data to determine the savings in fuel, truck hours, and maintenance costs. These savings were extracted together with other data, such as cycle time and total material through the haul road section for the study period from the mine records.

3.2.1 Research variables calculations

This research worked out the average fuel consumed before and after cement stabilisation. Equations 3-1 to 3-2 show the workings on how the fuel consumed was worked out. The net difference between the fuel consumed before and after is then worked out using Equation 3-3:

Average equivalent fuel consumed before stabilisation (A):

$$A=(T/P_1)x(F_1+G_1) \quad \text{Equation 3-1.}$$

Where: A is the average equivalent fuel consumed before stabilisation expressed in litres. T is the total material moved in tonnes through CW5-Ramp1 and P_1 is the average truck payload before stabilisation in tonnes. F_1 is the loaded truck fuel used before cement stabilisation in litres and G_1 is the empty truck fuel used before cement stabilisation in litres.

Average fuel consumed after cement stabilization (B):

$$B= (T/P_2)x(F_2+G_2) \quad \text{Equation 3-2.}$$

Where: B is the average fuel consumed after cement stabilization expressed in litres. T is the total material moved in tonnes through CW5-Ramp1, P_2 is the average truck payload after stabilisation in tonnes. F_2 is loaded truck fuel used after cement stabilisation in litres. G_2 is the empty truck fuel used after cement stabilisation in litres.

The value of the net fuel used is therefore given by (C):

$$C = (A-B)xP \quad \text{Equation 3-3.}$$

Where: C is the net fuel value consumed expressed in US dollars and P fuel price in dollars. A and B are deduced from Equations 3-1 and 3-2.

In Equation 3-1 and 3-2, the equivalent number of loads that would have been hauled through the road section was calculated by dividing the total tonnes moved by the average truck payload before stabilisation. In Strack (2015) a similar approach was used to calculate the annual traffic count that passed through a whole road. An operation that hauled 7.2 million tonnes annually using 220 tonne dump trucks was estimated to have handled 32,850 loads annually through that haul road. The fuel used for the haul and empty legs was then summed up and multiplied the number of loads through the section to work out the total fuel consumed.

Equation 3-2 used the same approach to work out the number of loads using the total tonnes moved divided by the average truck payload. The fuel consumption after was summed up for the haul and empty legs through the section and the sum multiplied by the number of loads to give the total fuel used through CW5-Ramp1. The net fuel used is therefore the difference between the Equations 3-1 and 3-2 to either give a saving or loss.

The equivalent truck hours used before cement stabilisation is evaluated using Equation 3-4 in which the total travel time is summed up for the haul and empty legs through the haul road section. This is then multiplied by the number of loads through CW5- Ramp1 to give the total hours travelled.

Equation 3-5 calculates truck hours after cement stabilisation. The difference between Equation 3-4 and 3-5 gives the net truck hours through CW5-Ramp1.

$$HT_1=(T_1/P_1)x((D_1+E_1)/3600))$$ Equation 3-4.

Where: T_1 is the total material moved in tonnes before stabilisation, P_1 is the truck average payload before stabilisation in tonnes D_1 is truck loaded travel time before cement stabilisation in seconds and E_1 is the truck empty travel time before cement stabilisation in seconds, and 3600= is the conversion factor from seconds to hours.

$HT_2=(T_2/P_2)\ x((D_2+E_2)/3600))$ Equation 3-5.

Where: T_2 is the material moved in tonnes, P_2 is the truck payload after stabilisation in tonnes and D_2 is the truck loaded travel time after cement stabilisation in seconds. E_2 is the truck empty travel time after cement stabilisation in seconds and 3600= is the conversion factor from seconds to hours.

Maintenance costs saved, MC_1, from truck hours is therefore calculated by:

$MC_1= (HT_1-HT_2)xM$ Equation 3-6.

Where M is the truck maintenance cost in US Dollars, HT_1 and HT_2 are calculated from Equations 3-4 and 3-5. The maintenance costs saved is expressed in US Dollars.

3.3 Chapter Summary

In this chapter, the area of interest at Lumwana Mine was stated with the extent of the study ramp defined. The methods of data collection used for the research was highlighted. The information on payload, fuel used, truck speed and travel time was accessed through the MaxMine system. A summary of how each of these parameters was worked out by MaxMine was presented in the chapter sections. A summary of how MaxMine calculates road condition was also brought out with the graphic representation of the haul road condition report shown. The methods through equations on how the research worked out fuel and maintenance truck hours savings were also discussed with the chapter forming a basis for upon which the analysis in Chapter 4 is built on.

4 DATA COLLECTED AND ANALYSIS

4.1 Introduction

This chapter describes all the data the author obtained on the construction and maintenance of haul roads at Lumwana Mine. The analysis of the collected data is also presented.

4.2 Input Data Sources

The primary data source for this study is restricted to a 300-metre section of Chimiwungo West 5 (CW5) Pit Ramp1 at Barrick Lumwana, constructed using Portland cement stabilisation. This ramp section is the primary access in and out of the pit, with a high traffic volume to the crusher and main waste dump. Data collected for this study for this ramp section include a brief overview of the construction methodology (detailed technical construction specifications fall outside the scope of this study). The construction methodology was obtained from the in-house road construction procedures. Haul road maintenance regime schedules were obtained from the mine weekly and grader plans. The performance monitoring results of the stabilised ramp sections were obtained from the mine haul road condition monitoring system called 'MaxMine' and field observations of the ramp condition at specified periods.

Haul road construction and maintenance cost details were obtained from the mine projects office. For each data set obtained for this section of the ramp under the study, a comparison was made with the ramp section before the Portland cement stabilisation technique was applied.

4.3 Haul Road Characteristics

4.3.1 Haul road geometry

CW5 Ramp1 was constructed at a gradient of 10% and a width of 40m. the width includes a provision for a safety berm on one side, with approximately 6m base on the open edge side. The stabilised section of the ramp starts after 100m from the top of the ramp and runs for a distance of 300m before it gets onto a right flat switchback into the next section of the ramp for another 300m. The ramp was built with a drain on the high wall side of the ramp within the same 40m width. This left the active running board at 32m at a cross fall of -3% towards the drain. The geometry of all other ramp sections built without the cement stabiliser is the same as the ramp under consideration in this study.

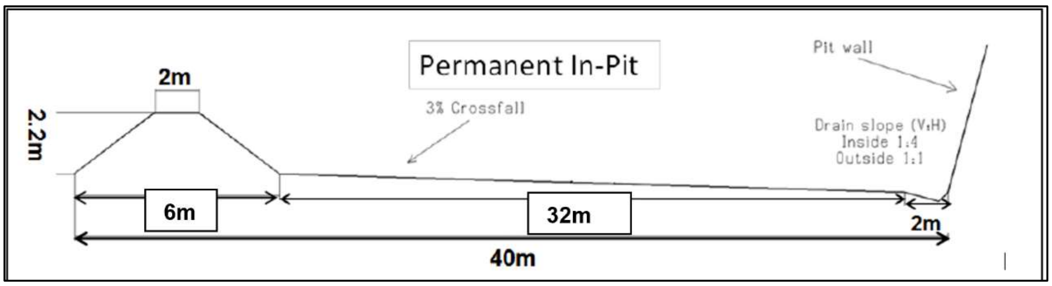


Figure 4-1. Haul road cross-section (Barrick Lumwana Mine, 2011)

4.3.2 Haul road materials and pavement layers

The ramp under consideration was constructed through an area with weak underfoot conditions characterised by saprolite material and some transitional rock in some places. Building a solid ramp system through such a ground profile required the site to be well-engineered. The area was therefore boxed out of the soft and weathered material to a depth of 4m to 6m and backfilled with competent gneiss rock, mainly from the pit ROM waste material. This rock formed the ramp sub-base layer, which was compacted by the weight of haul trucks as they dumped the material. After that, the ramp base and the running surface were constructed using 100mm crushed rock with 0-5mm fines added to provide binding properties and stabilised with Portland cement to a thickness of 400mm to 1,000mm in successive compacted layers between 200mm to 300mm.

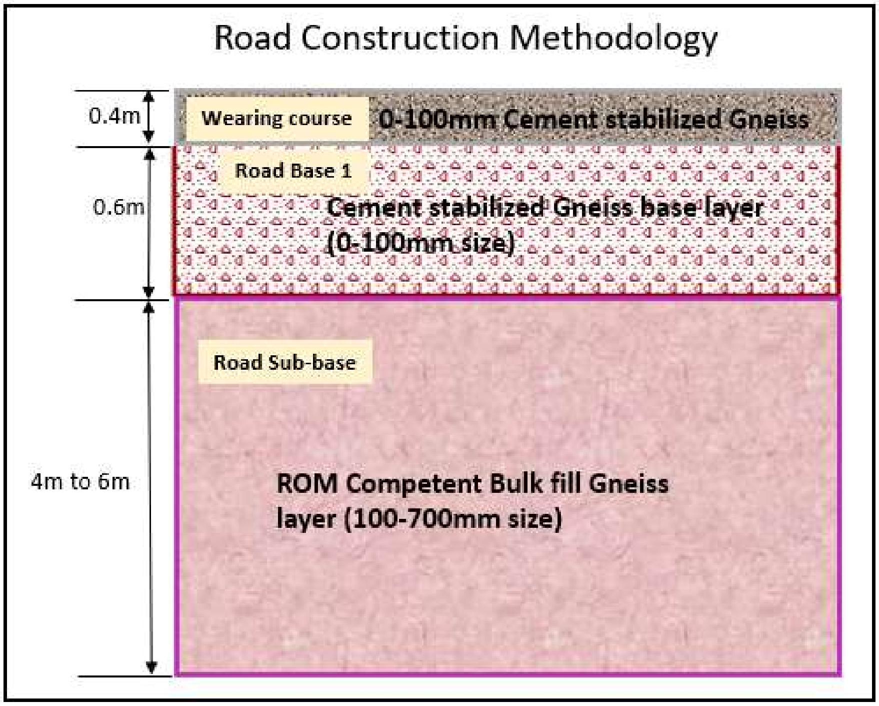


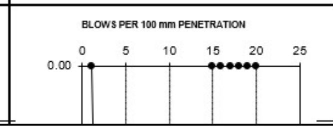
Figure 4-2. Cement stabilised haul road typical section (Barrick Lumwana Mine, 2020)

DCP tests were conducted on the ramp sections; three test results obtained are in Tables 4-1 and 4-2 and additional data in appendix D.

Table 4-1: DCP results along CW5 Ramp1 (Lumwana Mine Geotech, 2020)

DCP-CW5-RAMP01- 01					DCP--CW5-RAMP01-02			
Date tested			26-Jul-20		Date tested			3-May-20
Start Depth (mm)			0		Start Depth (mm)			0
Number of blows	Penetration per 10 blows (mm)	Depth from NGL (mm)	Penetration Rate (mm/blow)		Number of blows	Penetration per 10 blows (mm)	Depth from NGL (mm)	Penetration Rate (mm/blow)
0	0	0	0		0	0	0	0
5	1	-1	0		5	1	-1	0
	1	-1	0			1	-1	0
10	2	-2	0		10	1	-1	0
	2	-2	0			1	-1	0
20	2	-2	0		20	1	-1	0
	2	-2	0			1	-1	0
30	2	-2	0		30	2	-2	0
	2	-2	0			2	-2	0
40	2	-2	0		40	2	-2	0
	2	-2	0			2	-2	0
50	2	-2	0		50	2	-2	0
	2	-2	0			2	-2	0
55	2	-2	0		55	2	-2	0
	2	-2				2	-2	

Table 4-2: DCP & CBR values- CW5 Ramp1 (Lumwana Mine Geotech, 2020)

PROJECT Barrick- LMC			Chimi West 5 R1 Stabiiized Road			
PROJECT NUMBER:			377235mE; 8641807mN, 1349RL			
TEST LOCATION:			DCP 1			
STARTING DEPTH FROM N.G.L. (m)			0			
DATE			26-Jul-20			
NUMBER OF BLOWS	PENETRATION DEPTH [mm]	DEPTH FROM N.G.L. [m]	PENETRATION RATE [mm / blow]	BLOWS/ 100 mm PENETRATION	CORRELATED CBR VALUE ***	GRAPH
20	5	0.000	0	400	2385	
40	10	-0.010	0	400	2385	
60	18	-0.018	0	333	1892	
60	18	-0.018	0	333	1892	
60	18	-0.018	0	333	1892	

The DCP results show a maximum penetration of 2mm, after which no other penetration occurred. Therefore, the resulting penetration rate (mm/blow) obtained is 0. The obtained DCP values had correlated equivalent minimum CBR values of 865% to a maximum of 2385%. The obtained CBR values show a very hard surface which can handle heavy traffic. The higher the CBR value the harder the surface. High quality sub-bases will have values of 80-100% (Southern Testing , 2023). The over 800% obtained in this study shows that the obtained ramp was very competent.

Lumwana Mine (2011), through the haul road construction guidelines, was able to identify the road types and classifications used at Lumwana Mine. The classification was mainly based on their function, traffic categories, expected life span, and operational requirements. As a result, four main types and their characteristics were highlighted and summarised below.

Permanent haul roads

Permanent roads are the major arterial roads in the mine used by all mine traffic. The primary criteria for permanent haul roads are:

- Long-term major haul road, with a life expectancy greater than three months;
- Used by haul trucks and light vehicles;
- High-frequency constant traffic use;
- Formed construction; and
- Delineated.

Temporary -bench haul roads

Bench roads are temporary haul roads that usually extend from the base of the main ramp/haul road to the working face. The primary criteria for bench roads are:

- Short-term major haul road, with a life expectancy of fewer than three months;
- Used by haul trucks and light vehicles;
- High-frequency traffic use;
- Non-formed construction; and
- Delineated outside 80m from the operating face.

Temporary - dump roads

Dump roads are a type of temporary haul road located on the dump. They run from the permanent haul road to the dump face. The essential criteria for dump roads are:

- Short-term major haul road, with a life expectancy of fewer than three months;
- Used by haul trucks and light vehicles;
- High-frequency traffic use;
- Non-formed construction; and
- Delineated outside 80m from dumping face.

Light vehicle roads

Light vehicle roads may be permanent or temporary. They are access roads around the pit's perimeter, between permanent and bench haul roads, and on the surface. The essential criteria for light vehicle roads are:

- Generally long-term road, with a life expectancy greater than three months;
- Used by light vehicles and service vehicles only;
- Low-frequency traffic use;
- Formed construction, if permanent; and

- Delineated.

Construction of unstabilised haul roads on the mine is done by undercutting the ramp by a minimum depth of 2m. The depth of how much to cut out depends on the underfoot conditions and results of the geotechnical sampling. The Haul Road Construction Detail Guidelines define in details the geometry of the mine haul roads. The pavement layers for haul roads are usually determined by empirical methods. These methods often vary from time to time depending on such factors as the quality of ROM material available from the pit, the category of the haul road being constructed, etc. The construction methods have been refined over time so that the teams on the ground can know what works or not.

4.4 Haul Road Maintenance Regime

The cement-stabilised ramp in this research underwent minor maintenance for six months from the day it was opened up to heavy traffic. The little maintenance incurred during this period involved light grading. The frequency of such grading to skim off soft mud from the haul truck tyres was once every two weeks in the last two wet months from November 2020 to December 2020. In the first four months of dry weather from July 2020 to October 2020, no grading took place.

The haul road maintenance regime on the mine for typical haul roads and ramps that are not stabilised comprises grading undulating areas with motor graders and reconstructing worn-out layers. Grading of the haul roads follows a grader plan issued once every 24 hours, with each road section graded at least once daily. The grading conducted on haul roads and ramps causes the wearing coarse of the ramps to be skimmed off in successive layers per grader pass. With time and continuous grading, the wearing course, about 300mm minimum of crushed rock, gets eroded, thereby exposing the base. Such a scenario causes more undulations on the haul road as soft spots give in under the loading effect of haul trucks. The disintegrated wearing coarse, and the base are replaced to maintain a smooth running surface. This process is a haul road rebuild process in which some sections of the road base with soft spots are rebuilt with competent ROM waste material before a uniform application of the running course material is placed. Doing this on a busy mine haul road is challenging as production haul trucks have to use a single lane at a time, meandering around heavy mobile equipment such as graders and dozers.

The rebuild process increases cycle time as haul trucks move slowly, causing a loss in production during haul road construction. The time it takes to rebuild a failed haul road section depends on the severity. However, it has been established from practice that a 100m section of a single 16m lane would take about 16 hours. This time includes approximately 6 hours of skimming off and digging out soft disintegrated material up to 1m in thickness and 5 hours of replacing the this material with competent rock, and another 5 hours of building the running course with the crushed stone while grading and compacting. It, therefore, requires not less than 32 hours to rebuild both lanes of a 100m section of the failed haul road.

A busy haul road can be rebuilt during the dry months at a frequency of once every three months, while in the wet season, the frequency can reduce to once a month, with some sections requiring only the running course of crushed rock at the same frequency to be rebuilt.

4.5 Haul Road Construction and Maintenance Costs

The haul road construction and maintenance costs covered in this section are segregated into two. These are the actual cost of construction incurred using the cement stabilisation method and those that would have been incurred on the construction and maintenance of the ramp section under review had it been constructed in a conventional way like all other ramps and not stabilised with cement. The construction costs for the two methods are the same up to the base. However, the running surface costs differ because one is stabilised with Portland cement, and the other is not.

The actual unit cost of haul construction with a cement stabiliser was $28 per square metre ($m^2$), while the unstabilised section of the same ramp would have cost $25 per m^2 (see Table 4.3). As can be seen, the additional cost attributed to the cement stabiliser was $3 per m^2. Therefore, the cost of stabilising a haul road with cement was 13% above the unstabilised cost. The cost of hauling and placing sub-base material delivered as ROM waste is not added in estimating the actual cost of road construction as it is already accounted for in the unit cost of mining. The sub-base ROM material would still be hauled to the waste dump if not used on the haul road.

Table 4-3 Haul Road construction costs (stabilised and unstabilised) (Lumwana Mine a, 2020).

Cement Stabilised Haul Road construction cost						
Item	Description	Qty	Unit cost ($/Unit)	Cost (USD)	Unit cost $/Sq.M of road constructed	Unit cost $/Tonne mined
1	Haul road length (m)	299				
2	Subbase cut to spoil tonnage	83,626	2.0	$167,252	17.5	0.002
3	Crushed running course tonnage	13,347	5.2	$69,406	7.3	0.001
4	Cement stabilisation costs	9,568	3.3	$31,670	3.3	0.000
	Total			**268,328**	**28.0**	**0.003**
UnStabilised Haul Road construction cost						
Item	**Description**	**Qty**	**Unit cost ($/Unit)**	**Cost (USD)**	**Unit cost $/Sq.M of road constructed**	**Unit cost $/Tonne mined**
1	Haul road length (m)	299				
2	Subbase cut to spoil tonnage	83,626	2.0	$167,252	17.5	0.002
3	Crushed running course tonnage	13,347	5.2	$69,406	7.3	0.001
	Total			**236,658**	**24.7**	**0.002**

4.6 Haul road maintenance costs

Haul road maintenance costs include the cost of mining equipment used in haul road maintenance. This process involves cutting out soft haul road sections with a bulldozer, loading them with an excavator and haulage trucks then placing competent haul road reconstruction materials. The unit cost of maintaining a section of mine haul road length similar to this study but not stabilised with cement was $10 per square meter (Table 4-4). This cost includes cutting out any unsuitable material in soft areas that have given in or disintegrated. Crushed material (0-100mm in size) would have to be applied once every three months. The ramp constructed with a Portland cement stabiliser provided a resilient running surface that required very little maintenance in the form of light grader works at a frequency of once every two weeks for the wet months and no grading at all in the dry months. The six-month period under review consisted of an initial four months of dry and two months of wet months. Therefore, the ramp was maintenance-free for the first four months and was graded four times in the last two months.

Table 4-4 Haul road maintenance costs (stabilised and unstabilised) (Lumwana Mine a, 2020).

UnStabilised Haul Road maintenance cost						
Item	Description	Qty	Unit cost ($/Unit)	Cost (USD)	Unit cost $/Sq.M of road constructed	Unit cost $/Tonne mined
1	Haul road length (m)	299				
2	Subbase cut to spoil tonnage	20,907	2.0	$41,813	4.4	0.000
3	Crushed running course tonnage	8,008	5.2	$41,644	4.4	0.000
4	Grader hours	139	82.3	$11,482	1.2	0.000
5	Dozer hours	27.31	93.6	$2,557	0.3	0.000
	Total			**97,496**	**10**	**0.001**

Stabilised Haul Road maintenance cost						
Item	Description	Qty	Unit cost ($/Unit)	Cost (USD)	Unit cost $/Sq.M of road constructed	Unit cost $/Tonne mined
1	Haul road length (m)	299				
2	Subbase cut to spoil tonnage		2.0	$0	-	-
3	Crushed running course tonnage		5.2	$0	-	-
4	Grader hours	6	82.3	$510	0.05	0.000
5	Dozer hours		93.6	$0	-	-
	Total			**510**	**0.05**	**0.000**

The study found stabilised haul road maintenance costs for the section under review to be 99.5% cheaper than the unstabilised option at $0.05 a square meter compared to $10 per square meter on the unstabilised portion. This is because the stabilised ramp section only required minor grading, while the unstabilised area needed a haul road reconstruction program every three months in addition to daily grading. The road reconstruction program involves using mining equipment to cut and haul unsuitable material in soft spots, backfill with competent rock, shape and reprofile the haul road to required camber, and shape the running surface with crushed aggregate.

4.7 Gains in fuel savings and speed

The study utilised MaxMine-measured metrics to determine gains accrued from fuel savings, speed increase, and payload increase. Tables 4-5 and 4-6 bring out the summary of these gains.

Table 4-5 Recorded gains on a truck-loaded haul (Resolution Systems, 2021)

		Speed	Runs in sample	Time through section	Mean Payload	Entry speed	Entry throttle	Full throttle through haul	Fuel used
		(km/h)	(count)	(s)	(T)	(km/h)	(%)	(%)	(L)
Haul	before	12.1	1091	91.5	243.3	10.7	99.3	90.8	11.75
	after	13.6	107	81.3	254.9	17.2	99.3	95.5	10.62
	change	12%	-	-11%	5%	62%	0%	5%	-10%

Table 4-6 Recorded gains on empty truck return (Resolution Systems, 2021)

		Speed	Runs in sample	Time through section	Mean Payload	Entry speed	Entry throttle	Full throttle through haul	Fuel used
		(km/h)	(count)	(s)	(T)	(km/h)	(%)	(%)	(L)
Return	before	23.9	1623	48.8	0.0	26.9	24.1	0.5	0.38
	after	34.5	717	33.0	0.0	33.1	35.0	5.5	0.33
	change	45%	-	-32%	-	23%	45%	1072%	-14%

4.7.1 The value gained from diesel savings

The analysis of the Lumwana cement stabilised 300m ramp section shows that there is an average 10% gain in fuel usage on a loaded haul and 14% on the empty return leg. The total material hauled through the haul road section during the study period was 20.6 Mt (Lumwana Mine, 2021). The study evaluated fuel in the form of diesel saved using equation 3-1 to 3-3 and in Table 4-7.

The total material moved of 20.6 million tonnes (Mt) is used in this calculation to work out the equivalent load cycles that passed through the haul road section which is then multiplied by other variables to obtain the fuel used. The study worked out an equivalent amount of fuel that would have been used before cement stabilisation to move the same tonnage using Equation 3-1. This calculation requires the use of the tonnage hauled after stabilisation in order to obtained a like for like comparison in understanding how much fuel would have been used if the same tonnage was hauled at previous values of payload and fuel consumption.

The average equivalent fuel consumed before stabilisation (A) was 1,031,000 litres using Equation 3-1. See details in Table 4-7

Table 4-7: Fuel Input variables table before cement stabilisation

S/N	Input Variable	Description	Value
1	T	Material moved in tonnes	20,600,000
2	P1	Truck payload before stabilisation in tonnes	243
3	F1	Loaded truck fuel used before cement stabilisation in litres	12
4	G1	Empty truck fuel before cement stabilisation in litres	0.4

The average fuel consumed after cement stabilization (B) was 887,000 litres using Equation 3-2 (see details in Table 4-8)

Table 4-8: Fuel input table after cement stabilisation

S/N	Input Variable	Description	Value
1	T	Material moved in tonnes	20,600,000
2	P2	Truck payload before stabilisation in tonnes	255
3	F2	Loaded truck fuel used before cement stabilisation in litres	11
4	G2	Empty truck fuel before cement stabilisation in litres	0.3

Therefore; using Equation 3-3, the fuel saving was $130,000 (see details in table 4-9)

Table 4-9: Fuel savings input table

S/N	Input Variable	Description	Value
1	C	Fuel savings in liters	144,000
2	P	Fuel price in US dollars	0.9

The study worked out fuel savings of 142Kltrs which is attributed to haul trucks efficiency due to reduced travel time through the section which reduced by 26 seconds for combined haul and empty runs.

From the analysis above, US $130,000 was saved on diesel usage due to using a Portland cement-stabilised section of the haul road.

4.7.2 The value gained from truck speed gain

MaxMine (2021), Lumwana cement stabilisation analysis determined an average 45% gain on the empty return speed and 12% gain on the loaded haul speed. In addition, positive gains on the travel time through the section were recorded at 32% gain for the empty return leg and 11% for the loaded haul. Table 4-10, using Equations 3-4 and 3-5, shows total truck hours through CW5 Ramp1 before and after cement stabilisation respectively. In this regard, the total maintenance cost saving was $111,000.

Table 4-10 Truck hours gained from increased speed (Lumwana Mine, 2021; Resolution Systems, 2021).

Equivalent truck hours before due to speed (HT1)	
Total Material Moved (Tonnes)	20,600,000
Payload before (Tonnes)	243
No. of cycles before (No.)	85,000
Loaded truck travel time before (sec)	92
Empty truck travel time before (sec)	49
Total time per cycle (Sec)	140
Total time per cycle (hr)	0.04
Total truck hours before (hr)	3,300
Truck hours used after due to speed (HT2)	
Total Material Moved (Tonnes)	20,600,000
Payload before (Tonnes)	243
No. of cycles before (No.)	85,000
Loaded truck travel time after (sec)	81
Empty truck travel time after (sec)	33
Total time per cycle (Sec)	114
Total time per cycle (hr)	0.03
Total truck hours after (hr)	2,700
Truck hours saved (HT1-HT2)	600
Truck maintenance cost per hour (US$)	185
Haul truck maintenance cost saved - from speed (US$)	111,000

The truck hours saved from travel time are worked out using equations 3-4 to 3-6.

The study evaluated the number of cycles to move the 20.6Mt ROM material that passed through the haul road section under review to be 85,000 cycles. The total time saved per cycle due to the reduced travel time was 0.01hrs giving a total truck hour gain of 600 hours. At a truck maintenance cost per hour of $185, the truck maintenance cost savings for hauling through the cement-stabilised section of the haul road was $111,000.

The total value gain from fuel, speed, and payload are summarised in table 4.11 as $241,000.

Table 4-11 Cement stabilisation value gain (Lumwana Mine, 2021; Resolution Systems, 2021).

Area of Savings	**Value Saved (US$)**
Diesel savings	$ 130,000
Haul truck maintenance cost- from speed	$ 111,000
Total value saved over the segment	**$ 241,000**

4.7.3 Rolling resistance calculation

Before cement stabilisation

The rolling resistance was worked out using the qualitative assessment tools and method discussed in section 2.7.3 for reasons outlined in the same section that apply to mine haul roads. The roughness defect score sheet was done before stabilisation and the values tabulated below

Table 4-12: rolling resistance before cement stabilisation

MINE HAUL ROAD ROLLING RESISTANCE VISUAL EVALUATION						
DATE	27-03-2019		EVALUATOR		BK	
ROAD	CW5 Ramp1		VEHICLE SPEED km/hr(V)		12	
CHAINAGE	0 to 300m		TRAFFIC kt/day			
DEFECT	**RDS (Rolling resistance)**					
	DEGREE (1-5)		**EXTENT (1-5)**		**DEFECT SCORE**	
Potholes	3	x	3	=	9	
Corrugations	5	x	4	=	20	
Rutting	5	x	4	=	20	
Loose Material	4	x	4	=	16	
Stoniness- Fixed	4	x	4	=	16	
TOTAL ROUGHNESS SCORE (RDS)					**81**	
ESTIMATED ROLLING RESISTANCE (%) Refer to graph for rolling resistance percentages					**3.4%**	

The rolling resistance before stabilisation is therefore estimated at 3.4%.

After cement stabilisation

The roughness defect score sheet was done after stabilisation and the values tabulated below

Table 4-13: Rolling resistance evaluation after cement stabilisation

MINE HAUL ROAD ROLLING RESISTANCE VISUAL EVALUATION					
DATE	27-09-2020		EVALUATOR		BK
ROAD	CW5 Ramp1		VEHICLE SPEED km/hr(V)		12
CHAINAGE	0 to 300m		TRAFFIC kt/day		
DEFECT	**RDS (Rolling resistance)**				
	DEGREE (1-5)		**EXTENT (1-5)**		**DEFECT SCORE**
Potholes	1	x	1	=	1
Corrugations	1	x	1	=	1
Rutting	2	x	2	=	4
Loose Material	2	x	2	=	4
Stoniness- Fixed	2	x	2	=	4
TOTAL ROUGHNESS SCORE (RDS)					**14**
ESTIMATED ROLLING RESISTANCE (%) Refer to graph for rolling resistance percentages					**2.1%**

The rolling resistance after stabilisation is therefore estimated at 2.1%.

4.7.4 Improvements on the Haul road condition

The MaxMine Haul Road Condition (HRC) report system is used by the mine to measure the condition of haul roads as detailed in Chapter 3. The study compared HRC data before and after cement stabilisation, and Figure 4-3 highlights the outcome.

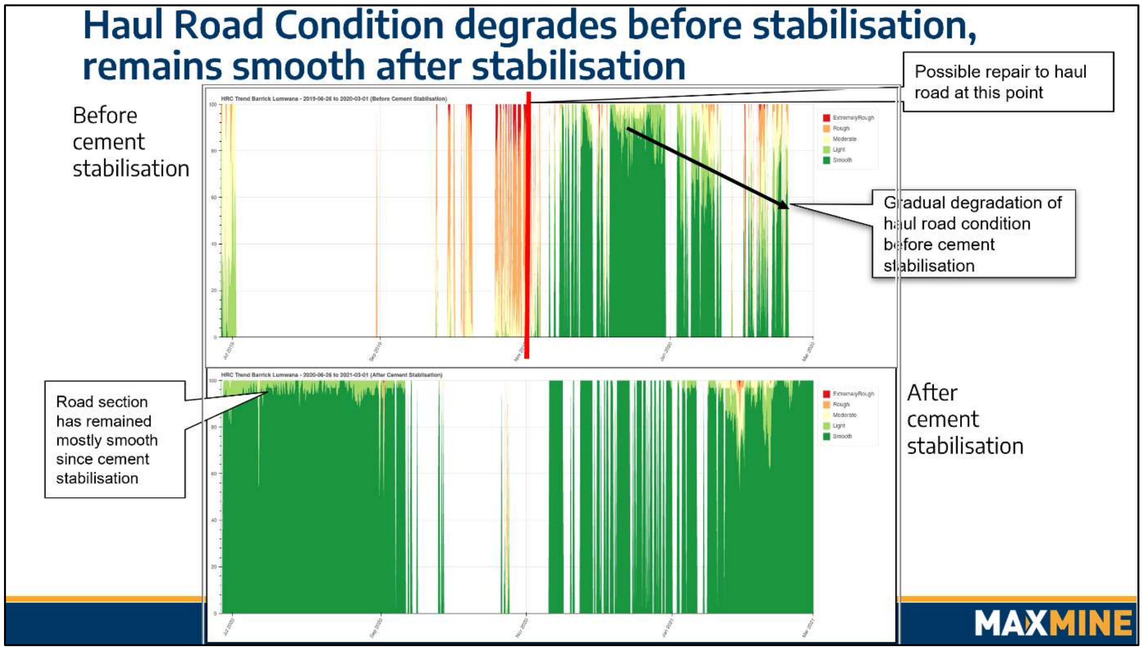


Figure 4-3. Haul road smoothness comparison before and after cement stabilisation (Resolution Systems, 2021).

Figure 4-3 shows that the haul road section underwent a gradual degradation in its condition before cement stabilisation and remained consistently smooth after cement stabilisation. The smooth conditions explain the low maintenance incurred on the haul road, as it was in good condition. Furthermore, the excellent condition enabled increased speed, payload, and fuel efficiency as the haul truck drivers moved confidently without any reports of sliding/slipping or getting stuck.

4.8 Data Analysis

This section will discuss the economic benefits of constructing haul roads using cement stabilisation based on the above data collected in the Lumwana Mine case study.

Table 4-3 shows that the cost of building the road section under review using the Portland cement-stabilised method was less than $0.003 per tonne mined. The ramp section under consideration constituted 8% of the length of the mine ramp system that was in use for the 2020 period. If the cost of constructing this ramp under review is extrapolated over the whole 3681m, the unit cost comes close to $0.03 cents per tonne mined to build a stabilised ramp system for the mine. The calculation for this extrapolation is shown below:

Cost to build 299m of cement stabilised road $268,328

Cost to build 3681m = ($268,328 x 3681m)/299

= $3,303,000

Total tonnes mined= 100,359,127

Unit cost of building cement stabilised haul road= $3,303,000/100,359,127

= $0.03/t

This cost, about 1% of the mining unit cost, is minimal compared to the broader benefits already highlighted above and summarised in Table 4-14.

The rolling resistance of the haul road was reduced from 3.4% to 2.1%. This was an enabler for quick passage through the ramp and enabled trucks to move without burning more fuel and also improved the cycle time.

Table 4-14 Cement stabilisation value gains summary (Lumwana Mine, 2021; Resolution Systems, 2021).

	Total Cement stabilisation delivered value Summary			
		Cement stabilised Haul road	**Unstabilised Haul road**	**Net Savings**
S/N	**Description**	**Amount (US$)**	**Amount (US$)**	**Amount (US$)**
1	Construction costs	-$268,328	$236,658	-$32,000
2	Maintenance costs	-$510	$97,496	$97,000
3	Gains from fuel-diesel			$130,000
4	Maintenance costs gains from truck speed			$111,000
	Total			$306,000
	Total Value delivered			**$306,000**

The overall value delivered by the 300 meters of common overlap of cement stabilisation was approximately $300,000. The cost of construction of cement stabilised compared to non-stabilised haul road was more by 13%. The maintenance cost between the two haul roads differs significantly by 99.5%, indicating an insignificant amount towards maintenance in light grading when the road is stabilised with cement. A total of 133 grader hours were saved in maintaining a 299m stretch of haul road over six months.

To grade 3681m unstabilised haul road, Equation 4-1 will be used to calculate the required grader hours.

$$\text{Hours} = A \times U \times D \times M \times Ma \times 0.65 \qquad \textit{Equation 4-1}$$

Grader hours for 6 months continuous grading was calculated to be 1800 hours while grader hours for 4 days of grading (reduced grading hours after cement stabilisation) were 40 hours.

Grader hours saved were therefore 1760 hours.

Table 4-15: Grader hours input table

S/N	Input Variable	Description	Value
1	A	Grader Availability	75%
2	U	Grader Utilisation of Availability	85%
3	M	Average number of days in a month	30
4	Ma	Actual number of months	6
5	0.65	Average number of grader units for CAT 24 grader parameters	0.65

If all major haul roads of about 3,681m in length were to be stabilised with cement, the maintenance cost of haul roads will go down as a total of 1,760 grader hours would be saved. The saving would allow more attention to be paid to the in-pit spine or bench haul roads, thereby contributing to increasing the operations' productivity as these areas will be smoother, allowing trucks to move at a higher speed.

Constructing more haul roads with cement will also increase the benefits from reduced usage of other ancillary equipment such as dozers and trucks and haul road construction materials such as crushed road base aggregates. In addition, the benefits from fuel efficiencies, payload, and truck speed increase, will also increase with the Portland cement-stabilised haul road increase.

4.9 Chapter Summary

Data collected was from CW5 Ramp1, which was constructed using the Portland Cement stabilisation method. Data collected included the haul road geometry, construction materials, and configuration of pavement layers. Haul road maintenance costs were found to be cheaper for the stabilised section than before it was by 99.5%. Analysis of the data collected showed accrued gains in fuel savings, payload and speed increases were also brought out from sections 4.7.2 to 4.7.5. Improvements on the surface smoothness of the haul roads were also highlighted, creating an environment for increased productivity. The benefits in value gain was an overall $306,000 which outweighed the input cost. This a positive gain as highlighted in table 4-14 where the construction and maintenance costs have been taken into consideration. The results and analysis of the data collected form key components of the research findings and conclusions.

5 CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

This chapter discusses and analyses a conclusion to the findings, and appropriate learnings are deduced. The chapter will further highlight the challenges encountered and other limitations encountered through the application of this method. Finally, recommendations for other areas of study and improvements, as well as how best to get around all encountered challenges, will be made.

5.2 Summary of Chapters

Haul trucks are the major equipment used to transport ore and waste material between various locations in a surface mine operation and account for more than 50% of the mining costs. The elements of this cost include expenditure on fuel, tyres, and scheduled maintenance based on accumulated engine hours on the haul trucks. Any improvements that optimise a mine operation's haulage system significantly impact the cost and productivity of such an operation. This study identified an improvement in the mine haul road network as key to delivering value and production efficiency. Portland cement stabilisation of the CW5 Ramp1 improved the haulage through that ramp. This improvement created an environment for efficiency through increased truck speed and payload and reduced fuel consumption.

This thesis has presented five chapters that cover the following, Chapter 1 is the introduction, which presented the research background and set the context highlighting the problem statement, justification for the research, setting the objectives and research scope as well defining the data sources. The background to the research highlighted the current haul road construction practices at Lumwana Mine and outlined the current challenges being faced. The geology formation and its suitability for road building material was discussed. The context set in the introduction led to the formulation of the problem statement, research objectives and scope.

Chapter 2 is the literature review that highlighted relevant literature on mine haul roads. The cost elements that are key in haul road construction were discussed and the benefits of having a good haul road network as well as how it impacts mining parameters such as fuel, maintenance costs and cycle time were also discussed- a good road help reduce the mining unit cost and can be achieved through improved haul road design, construction and maintenance. Haul road geometry and pavement layers as well road stabilisation techniques are also highlighted, cement stabilisation was identified as one of the methods which improves haul road pavement layers. Good road geometry has a uniform gradient, good turning radius and build to keep water away from the running surface. Rolling resistance and different methods of measuring it were discussed with the difference between mine haul road and highway rolling resistance identified. Rolling resistance in the mine haul road is little impacted by air drag due to the low speeds but most impacted by the surface conditions- a different method of evaluating it was thus discussed.

Chapter 3 is the research approach/methodology which discussed the methods used in the study. The area of study in CW5 Ramp1 in Lumwana mine is defined and data obtained from the mine records and MaxMine was described. The Equations for interpreting the research data obtained were developed for use in the analysis in Chapter 4.

Chapter 4 was about the data obtained and analysis for the study which outlined all the data obtained on the cost of haul road construction and maintenance at Lumwana Mine. Using Equations 3-1 and 3-2 the savings made on diesel in the 290t trucks was 10% when loaded and 14% on the empty cycle. It was also observed that the travel time on the cemented segment of the ramp was 81 seconds when loaded and 33 seconds when empty which provided a good framework for reduced cycles time. It was also observed that the full throttle through the loaded haul component of the cycle time increased by 5% and the entry speed into the ramp increasing by 62%. These positive gains demonstrate the improved running surface as a result of the cement stabilisation. The rolling resistance worked out using the qualitative visual evaluation method showed a reduction from 3.4% before cement stabilisation to 2.1% after cement stabilisation.

5.3 Research Observations

The study utilised the capabilities of MaxMine, independent fleet management and optimisation system installed on the mine haul trucks, to determine the gains in truck speed, travel time, payload, road surface smoothness, and fuel efficiency. The study used the haul truck data downloaded from the MaxMine system to analyse the gains over six months. A total of 661 meters of ramp section was stabilised with Portland cement, and 300 meters of this ramp section provided a common overlap of MaxMine data before cement stabilisation. The balance of the 661 m could not be used in the study as there was no common overlap data to provide a like for like comparison.

The Portland Cement stabilised ramp proved to be resilient and robust enough as it was able to withstand traffic volume of 84,000 truck trips without deformation over six months. The ramp supported mine production positively as there was an increase in truck speed, a reduction in travel time, and a smooth flow of traffic without trucks getting stuck. Ramp maintenance through reconstruction and grading was also reduced giving a positive benefit in resources and time. The maintenance cost for the cement stabilised section was reduced from $10 per m2 to $0.05 per m2 as the grading frequency was reduced from 3 times a day to 4 times in 6 months. This allowed for more time for mine production as the ramp was available without lengthy haul road maintenance interference over the period of the study.

5.3.1 Key findings and observations

The study concluded that Portland Cement stabilisation of the haul road section of CW5 Ramp1 at Lumwana mine yielded positive results. There was a 12% increase in the haulage speed of loaded trucks from 12 km/h before cement stabilisation to 14 km/h. In addition, the return speed increased by 45%, from 24 km/h to 35 km/h. There was also a reduction in fuel consumption of 10% on the loaded haul and 14% on the empty return..

The study further observed a 5% increase in full throttle use on the loaded truck and a further 62% increase on the entry speed to the ramp on the loaded haul. This set the momentum required to move at a higher speed and less fuel consumption through the section of the ramp under the study. Entry speeds into the ramp segment and full throttle position on the return empty haul were even more at 23% and 1072% respectively. The results demonstrated the confidence the haul truck operators had in driving through the haul road section under study.

The overall financial gains for a 300 m Portland Cement stabilised haul road section computed amounted to US $306,000. The cost of haul road construction increased by 13%, but this cost was offset by the gains made from haul road maintenance costs which were reduced by 99.5%. In addition there were savings of 12% on fuel consumption and 21.5% reduction in truck tavel time.

5.4 Research Contributions

The study brought out an understanding of the financial benefits of cement stabilisation in mine haul road construction with respect to fuel consumption, and haul road and truck maintenance costs. The study, therefore, concluded that constructing haul roads with cement stabilisation delivers cost savings to a mining operation. In addition, it also promotes efficiency in mining and acts as an enabler for achieving mining targets. In the case of the cement stabilised haul road section in the study and based on the life of mine plan, it will continue to deliver economic gains for the remainder of the life of mine as it will remain in use till the year 2024.

5.5 Research Limitations

In this study, cost savings on haul truck tyres was not included because during the period under review and beyond, the mine carried out several front tyre rotations as a strategy to generate enough stock for use in the rainy season. The tyre consumption data would have therefore been skewed had it been used. Savings on tyre life gains could not therefore be accurately determined.

Even though more than 660m of ramp was built using the cement stabiliser, only 300 m of it could be used in the research for purposes of data comparison. The 300 m provided common overlap for easy comparison of data.

5.6 Recommendations for Future Research Work

The following recommendations provide an opportunity for improvement of similar studies in the future:

- Future studies must incorporate tyre life cost.
- Other forms of stabilisation, such as potash-Portland cement mix, should be explored in the future.
- In this study a motor grader was used to mix the haul road cement. However, the method requires an experienced grader operator to achieve an even mix and may also be a slow process. Therefore, it is recommended to use specialised material mixing equipment such

as the soil stabilisation mixer to ensure an even mix and spread of the stabilisation materials at a faster application rate.

- This study considered a haul road segment where ordinary Portland cement was used for stabilisation. Unfortunately, this required a minimum of 7 days of curing before a segment is opened up for regular usage. The curing time can be a considerable constraint in a mining operation if no alternative access is available. Therefore, it is recommended that future studies explore the use of fast-setting cement in stabilising the haul road pavement layers to reduce the curing period as much as possible.

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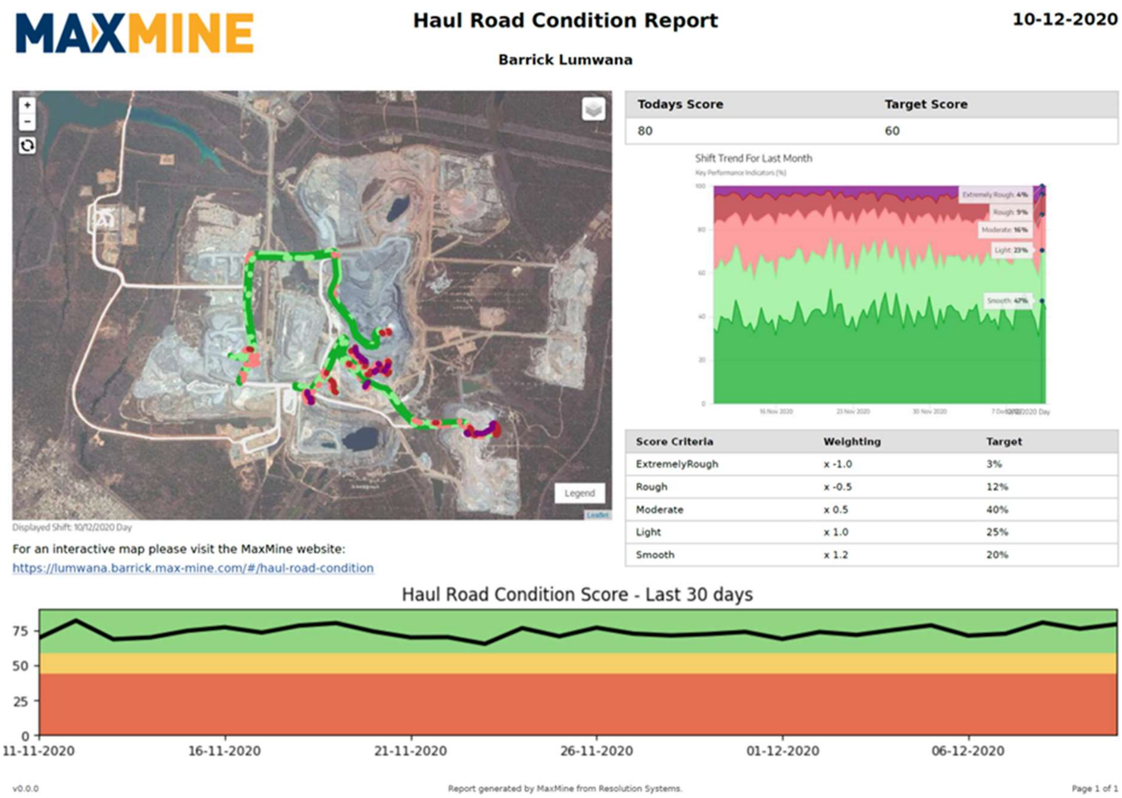
APPENDICES

APPENDIX A: MAXMINE ROAD CONDITION REPORT


Haul Road Condition Report

10-12-2020

Barrick Lumwana

Todays Score	Target Score
80	60

Score Criteria	Weighting	Target
ExtremelyRough	x -1.0	3%
Rough	x -0.5	12%
Moderate	x 0.5	40%
Light	x 1.0	25%
Smooth	x 1.2	20%

Figure A-0-1. MaxMine road condition report (Lumwana mine b, 2020).

APPENDIX B: ROAD MAINTENANCE GRADER HOURS CALCULATION FOR UNSTABILISED RAMP SECTION.

Table B-0-1 Unstabilised maintenance grader hours (Lumwana Mine a, 2020)

Grader requirements estimation	Length (m)	Width (m)	Areas	Area (m2)	Passes/ day	Grading Speed (km/hr)	Productivity (m2/hr)	Grading Hours/day
Bench area (inpit spine road)	-	32	6	-	3	3.5	15044.4	0.00
Dump area (Dump spine road)	-	32	2	-	1	3.5	15044.4	0.00
High Density Road areas	281	32	1	8,992	2	5.4	23211.36	0.77
Medium Density Road areas	-	32	2	-	1	5.4	23211.36	0.00
ROM Pad Spine	-	32	1	-	1	5.4	23211.36	0.00
Low Density	-	32	1	-	1	9.2	39545.28	0.00
Total	**281**			**8,992**				**0.77**
Grader Parameters	24M						Operating Units	0.03
Mouldboard width (m)	7.3						Available Units	0.04
Effective pass width (m)	5.873						Installed Units	0.05
Overlap (m)	0.5						Rounded up Installed	1.00
Grading Efficiency (%)	80%						Grader hours per month	23
Utilization (Grading Time/Available time)	85%						Grader hours for 6 months	139.462746
Availability	75%							

APPENDIX C: ROAD MAINTENANCE GRADER HOURS CALCULATION FOR STABILISED RAMP SECTION.

Table C-0-1 Stabilised road maintenance grader hours (Lumwana Mine a, 2020)

Grader requirements estimation	**Length (m)**	**Width (m)**	**Areas**	**Area (m2)**	**Passes/ day**	**Grading Speed (km/hr)**	**Productivity (m2/hr)**	**Grading Hours/day**
Bench area (inpit spine road)	-	32	6	-	3	3.5	15044.4	0.00
Dump area (Dump spine road)	-	32	2	-	1	3.5	15044.4	0.00
High Density Road areas	281	32	1	8,992	2	5.4	23211.36	0.77
Medium Density Road areas	-	32	2	-	1	5.4	23211.36	0.00
ROM Pad Spine	-	32	1	-	1	5.4	23211.36	0.00
Low Density	-	32	1	-	1	9.2	39545.28	0.00
Total	**281**			**8,992**				**0.77**
Grader Parameters	24M						Operating Units	0.03
Mouldboard width (m)	7.3						Available Units	0.04
Effective pass width (m)	5.873						Installed Units	0.05
Overlap (m)	0.5						Rounded up Installed	1.00
Grading Efficiency (%)	80%						Grader hours per month	3.10
Utilization (Grading Time/Available time)	85%						Grader hours for 6 months	6.20
Availability	75%							

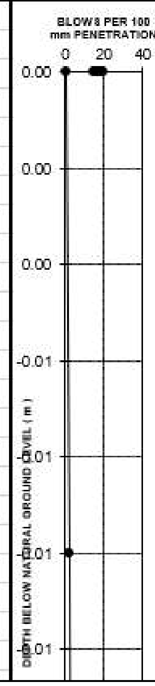
APPENDIX D: DCP AND CBR RESULTS ON CW5 RAMP 1

DCP AND CBR RESULTS ON CW5 RAMP 1.

Table D-0-1 Equivalent CBR results (Lumwana Mine Geotech, 2020)

PROJECT Barrick- LMC	Chimi West 5 R1 Stabiiized Road
PROJECT NUMBER:	377219mE; 8641792mN, 1354RL
TEST LOCATION:	DCP 1
STARTING DEPTH FROM N.G.L. (m)	0
DATE	26-Jul-20

NUMBER OF BLOWS	PENETRATION DEPTH [mm]	DEPTH FROM N.G.L. [m]	PENETRATION RATE [mm / blow]	BLOWS/ 100 mm PENETRATION	CORRELATED CBR VALUE ***	GRAPH
9	5	0.000	1	180	865	
18	10	-0.010	1	180	865	
40	18	-0.018	0	222	1130	
40	18	-0.018	0	222	1130	
40	18	-0.018	0	222	1130	



PROJECT	Barrick- LMC			Chimi West 5 R1 Stabiiized Road	
PROJECT NUMBER:				377235mE; 8641807mN, 1349RL	
TEST LOCATION:				DCP 1	
STARTING DEPTH FROM N.G.L. (m)				0	
DATE				26-Jul-20	

NUMBER OF BLOWS	PENETRATION DEPTH [mm]	DEPTH FROM N.G.L. [m]	PENETRATION RATE [mm / blow]	BLOWS/ 100 mm PENETRATION	CORRELATED CBR VALUE ***
20	5	0.000	0	400	2385
40	10	-0.010	0	400	2385
60	18	-0.018	0	333	1892
60	18	-0.018	0	333	1892
60	18	-0.018	0	333	1892

GRAPH

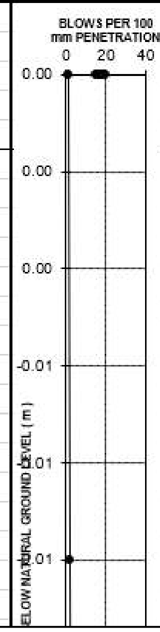


Table D-0-2 DCP results after stabilisation (Lumwana Mine Geotech, 2020)

DCP-CW5-RAMP01- 01			
Date tested			7/26/2020
Start Depth (mm)			0
Number of blows	Penetration per 10 blows (mm)	Depth from NGL (mm)	Penetration Rate (mm/blow)
0	0	0	0
5	1	-1	0
	1	-1	0
10	2	-2	0
	2	-2	0
20	2	-2	0
	2	-2	0
30	2	-2	0
	2	-2	0
40	2	-2	0
	2	-2	0
50	2	-2	0
	2	-2	0
55	2	-2	0
	2	-2	

DCP--CW5-RAMP01-02			
Date tested			5/3/2020
Start Depth (mm)			0
Number of blows	Penetration per 10 blows (mm)	Depth from NGL (mm)	Penetration Rate (mm/blow)
0	0	0	0
5	1	-1	0
	1	-1	0
10	1	-1	0
	1	-1	0
20	1	-1	0
	1	-1	0
30	2	-2	0
	2	-2	0
40	2	-2	0
	2	-2	0
50	2	-2	0
	2	-2	0
55	2	-2	0
	2	-2	

DCP--CW5-RAMP01 -03			
Date tested			7/26/2020
Start Depth (mm)			0
Number of blows	Penetration per 10 blows (mm)	Depth from NGL (mm)	Penetration Rate (mm/blow)
0	0	0	0
5	1	-1	0
	1	-1	0
10	1	-1	0
	1	-1	0
20	1	-1	0
	1	-1	0
30	2	-2	0
	2	-2	0
40	2	-2	0
	2	-2	0
50	2	-2	0

DCP-CW5-RAMP01 - 01			
Date tested			5/3/2020
Start Depth (mm)			0
Number of blows	Penetration per 10 blows (mm)	Depth from NGL (mm)	Penetration Rate (mm/blow)
0	0	0	0
5	1	-1	0
	1	-1	0
10	1	-1	0
	1	-1	0
20	1	-1	0
	1	-1	0
30	2	-2	0
	2	-2	0
40	2	-2	0
	2	-2	0
50	2	-2	0

DCP--CW5-RAMP01 -02			
Date tested			5/3/2020
Start Depth (mm)			0
Number of blows	Penetration per 10 blows (mm)	Depth from NGL (mm)	Penetration Rate (mm/blow)
0	0	0	0
5	1	-1	0
	1	-1	0
10	1	-1	0
	1	-1	0
20	1	-1	0
	1	-1	0
30	2	-2	0
	2	-2	0
40	2	-2	0
	2	-2	0
50	2	-2	0