Faculty of Engineering and Technology

Department of Mining and Geological Engineering

ASSESSMENT OF ECONOMIC AND ENVIRONMENTAL IMPACT OF FINES GENERATION AT MORUPULE MINE, BOTSWANA

by

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ABSTRACT

Coal mining causes various problems such as land subsidence, pollution of water sources, fines generation and air pollution. Mining companies spend a lot of money annually to mitigate the impact of fines generation. This study tried to identify the causes of fines generation at Morupule Cola Mine (MCM), estimate the amount of fines generated by the haulage system, and evaluate the economic and environmental impact of fines generation at MCM. Twelve coal samples of 20 kg each were collected from four mining sections and conveyor belts. They were tested for their mechanical and chemical properties to determine the properties that promote fines generation. The drop shatter test results show that the coal from section SM 3/1 is the most friable with 31.25% fines while the coal from SM 4/5 is the least friable with 15.5% fines. Also, the fines generated vary from 3% to 13%. The highest transfer point accounts for about 9% of the fines generation while the fastest conveyor belt and the whole haulage system from the working face to the runoff mine stockpile contribute 8% and 27% fines respectively. About 575 tonnes/shift of coal is lost due to blockages at the tail ends of conveyors. In terms of air quality and health hazard, the environmental impact of fines generation is negligible as the mine employs strict dust control measures. It is recommended that the height of transfer points be reduced, and deflection plates installed at the transfer points to minimise the impact of falling coal during conveying.

DEDICATION

In Memory of my Father

Mothowatsela Daniel Kabuku

ACKNOWLEDGEMENT

I wish to acknowledge my family for being there when I was doing this research. I thank my Supervisors, Professors Raymond S. Suglo and Bheemalingeswara Konka, for their dedication and contributions to my research, made it possible to finish this work. I am very grateful to them for that. I also want to appreciate the Department of Mining and Geological Engineering, the Department of Chemistry, and the Department of Environmental Science for allowing me to conduct my research in their laboratories. To Mr. Samuel Kgwarapi, Aobakwe Bayani and Victor Moffatt, your efforts in providing me with the necessary data have significantly contributed to this research. Finally, I thank all the workers Morupule Coal Mine for their support and co-operation during the data collection period. Most importantly, I want to appreciate my mother for her continual love and support.

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GENERAL INFORMATION ABOUT MINE

1. INTRODUCTION

Coal mining causes various problems such as land subsidence, damage to the water environment, fines generation, and air pollution. Mining companies spend a lot of money and time trying to reduce the effects of fines generation or coal degeneration. Coal degeneration is the reduction in the size of coal by interference leading to smaller particle sizes (Goodwin, 2017). Several factors affect coal degeneration which include the cutting techniques of the continuous miner, belt conveyor speeds, and drop heights of the transfer points and comminution of coal at the Processing Plant. Coal degradation results in coal dust that has environmental impacts such as pollution (water and air) as well as impacts on the health and safety of workers including the adverse effects on the mining equipment and machinery (Joseph, 2014). Handling operations from the working face to the stockpile increases the number of fines generated since factors such as abrasion during conveying come into play. This makes coal degeneration one of the most significant problems in coal handling.

Morupule Coal Mine (MCM) is an underground mine which employs room and pillar mining method to extract the coal. Continuous miners are used for cutting the coal. The mine produces metallurgical and thermal coal. After the screening process small-sized coal with fines goes to the wash plant, where the separation between coal and gangue takes place based on the differences in their densities. Medium to big-sized coal goes through the comminution and sizing processes. The primary consumers of thermal coal are Botswana Power Corporation (BPC), Botswana Ash and the Namibian power utility company (Nam Power). BPC requires coal products ranging from 3.35 mm to 32 mm and only allows up to 32% fines (-3.35 mm) in the final product. This makes coal handling easier at the power plant.

1.1 Background

The Morupule Colliery is situated in Palapye and is owned and operated by the Government of Botswana. The colliery was founded in 1973 to supply the Bamangwato Concessions

Ltd. with coal. However, the users of coal have increased over the years to include regional power plants and industries, the primary consumer being the Morupule Power Station.

In order to supply high quality coal to consumers locally and regionally, a small wash plant with a processing capacity of 120 tonnes/hour was built in January of 2008. The Botswana government supported this project as a way of empowering the local economy. The washed coal also results in less pollution from the power plant. A significant expansion to the colliery was carried out between 2010 and 2011. This was to supply coal to the adjacent BPC B Phase 1 Power Station (600 MW) that was under construction between 2010 and 2011. The power station currently helps Botswana to become self-sufficient in power generation. In 2010, about 84% of the country's power needs were imported, mainly from Eskom in South Africa. But Eskom has shown a phase-wise reduction in power supply starting in 2008. The colliery expansion resulted in an increase in coal production from less than 1 million tonnes to 2.8 million tonnes per annum.

Feasibility studies were conducted in 2008 after which the expansion project commenced. On-site construction began in September of 2010. The colliery initially had around 320 employees, and after the expansion, the number increased to about 480 employees. The development resulted in the opening of four operating sections in the mine. The number of continuous miners increased from 2 to 4, one on standby with two shuttle cars per section. As a result of the expansion a new crushing and screening plant were constructed to replace the old one, and the former offices and workshops were upgraded as well. A connecting pipeline was constructed to the North-South Carrier water pipeline about 15 km from Palapye to supply surface water to the mine. The coalfield consists of four main seams. However, only No. 1 seam is currently being mined using room and pillar mining method with Continuous Miners (CM). No pillar extraction occurs, and the mine design is conservative to prevent surface subsidence. The No. 1 Seam has an average thickness of 8.5 m, an average calorific value of around 23.5 MJ/kg (air-dry) and is located at about 80 m below surface. Production over the past seven years averaged 877,000 tonnes per year. Within the lease area of the mine, the coalfield’s resource is 5 billion tonnes in estimation (Anon., 2019).

1.2 Study Area

MCM is located along the Serowe-Palapye road as shown in Figure 1.1. Geologically the Morupule area is comprised of Karoo sedimentary rocks which form the eastern margin of the greater Karoo basin developed to the west of Morupule. These sedimentary rocks consist of shale, coal, and sandstone of the Middle and Lower Ecca Group. Botswana has significant reserves of coal on the east side of the country with 40 million tonnes of recoverable reserves that are proven (Anon., 2007).

Figure 1.1 Map of Botswana showing location of Morupule Coal Mine

1.3 Problem Statement

One of the problems MCM facing is the generation of fine coal particles during mining operations. It has an impact on coal production and the environment. MCM classifies coal fines as particles which are < 3.35 mm in size. When the composition of fines in the stockpiles constitute more than 20% of the overall stockpile, then the targets (fines should make only 0.5% of the coal feed into the plant) would not be met at the Wash Plant. This, in turn, affects customer demand as they require coal in the right particle sizes that do not contain high levels of fines. For example, BPC requires coal products with less than 32% fines. In the past, the MCM has suffered penalties (fines) from some customers because of high fines content in the coal supplied to them.

Fine coal particles also contribute to air pollution during the stockpiling process during which it emits a lot of fine dust particles. Other problems that MCM is facing include:

- Blocking of the tail end of the conveyors and blockages at the Wash Plant which forces the operations at the Wash Plant to be periodically stopped. This leads to losses in production.
- Fines generated from coal dust when inhaled by the miners increase the risk of developing black lung diseases and silicosis. Fines also increase the risk of coal dust explosions. As reported by Raghavan (2014), coal dust reduces visibility along the haul roads which can lead to accidents.
- Coal fines create consolidation problems as it tends to stick to the surfaces and surrounding particles which leads to blockages in the coal flow during processing and at the power plant.

The problem of fines generation has always existed in the mine and has some environmental impact. According to the environmental impact statement of the Morupule Colliery Expansion Project of 2008, coal dust monitoring results (1.5 mg/m^3 total weighted average) from samples taken above surface indicated that the World Bank Group limits of 0.15 mg/m^3 were exceeded.

1.4 Aim of the Research

The proposed research attempts to investigate and identify the factors that are leading to the generation of finer particles of coal and mineral matter; determine the production losses due to the increased fines generation, assess the impact of fines generation on MCM and find ways to reduce the amount of fines generation.

1.5 Objectives of Research

The main objective of this study is to:

- Identify the causes of fines generation between the working face and the run of mine stockpile in MCM.

The sub-objectives of this study are to:

- Determine the quantity of fines generated by the haulage system.
- Evaluate the impact of fines generation in MCM.

1.6 Expected Outcomes

The expected outcomes of this work include:

ii). Factors leading to the generation of coal fines will be identified, and solutions found to minimise the problem.

iii). Frequent stoppages of the conveyor belt and production losses will be minimised.

iiii). Penalties imposed on the mine for high fines in the coal production will also be minimised.

CHAPTER 2

LITERATURE REVIEW

2. INTRODUCTION

Botswana has extensive reserves of coal belonging to Karoo Supergroup. These deposits of coal stretch from the north to the south along the east side of the country. The Morupule and Mmamabula areas form vital coalfields. The thickness of the coal seam in Morupule ranges from 2 to 9.5 m. The Morupule coalfields consist of bituminous coal with high content of ash and sulphur, with no coking properties and are relatively not disturbed. Botswana coal is among the most friable in the Southern African region alongside Zimbabwe, and South Africa (Free State, South Rand and Transvaal) as shown in Figure 2.1, where the direction of the arrows shows increasing friability (Falcon, 1986).

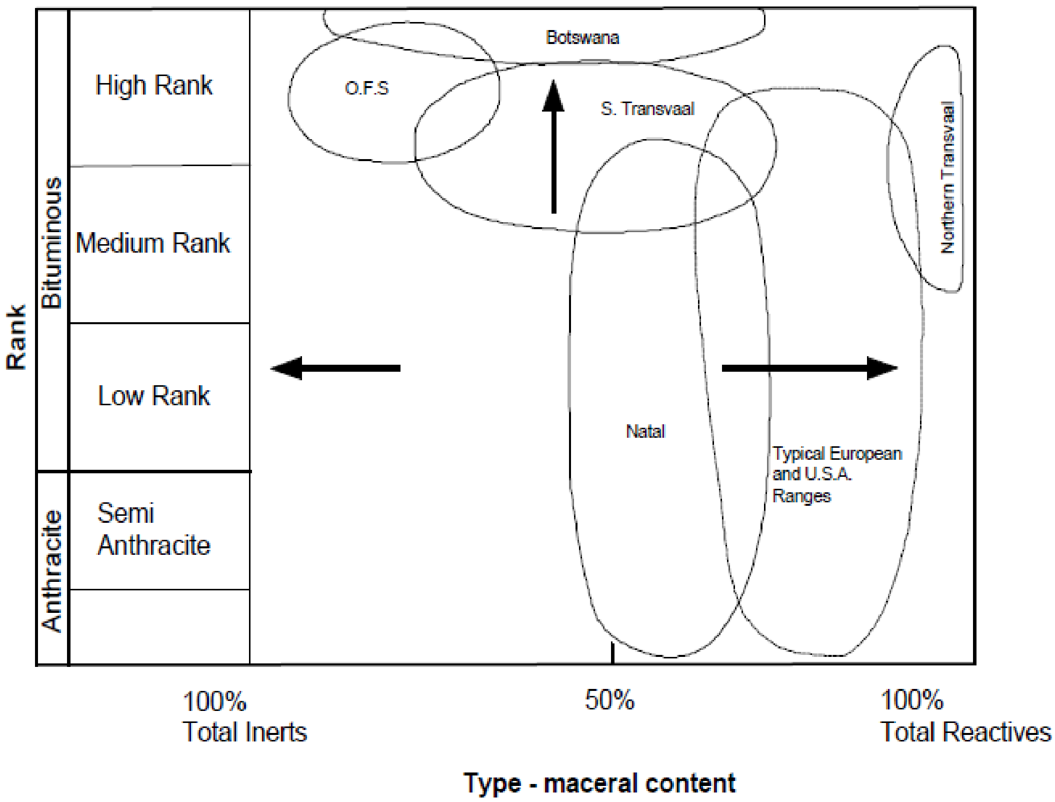

Figure 2.1 Coal Friability (Falcon, 1986)

2.1 Coal Formation

Coal is classified as a sedimentary rock formed from organic, inorganic material and water. It is formed from the partially decomposed remains of plant material that was initially deposited in a swamp, on the low-lying ground in deltas, alluvial plains and coastal environments and later covered by other sediments.

It is composed mostly of carbon ranging from 50 to 98%, hydrogen ranging from 3 to 13% and oxygen, and small quantities of nitrogen, sulphur, and other elements. Coal is composed of both organic and inorganic matter together with water, which are also known as macerals and minerals correspondingly (Sykorova, 2005). Generally, coals are known to be heterogeneous not only because they consist of macerals and minerals but also because they have other constituents such as moisture and microlithotypes.

2.2 Coal Analysis

Coal has a very intricate structure as a result of having both organic and inorganic constituents. It is difficult to entirely characterise coal due to its complex structure and the distribution of mineral matters within the coal carbon structure. This complexity of coal has led to different analytical techniques being established and designed to develop coal's potentials for utilisation. The designs of coal characterising analytical methods came about mainly to solve problems (e.g. abrasive wear) that arise with coal processing and utilisation (Raask, 1985).

Several analytical techniques are used to resolve questions like which components of coal lead to its abrasive wear, which coals are harder and which minerals are present in coals and how minerals are disseminated and associated with organic components of coals. Huggins (2002) divided these analytical techniques, particularly those used for characterising minerals in coals, into three different groups as methods that measure elemental concentrations present in the coal as ashes (e.g. X-Ray Fluorescence); methods that determine mineralogical components present in coals (e.g. X-Ray Diffraction) and methods that determine the macerals present in coals (e.g. optical microscopes).

2.2.1 X-Ray Fluorescence

X-ray fluorescence (XRF) operates by bombarding a sample material with high -energy X-rays from which it gets excited and emits characteristic fluorescent X-rays (Huggins, 2002).

It is used to measure the elemental concentrations present in the coal, mainly the inorganic component of the coal. It uses two fundamental processes - absorption or scattering of X-rays. The sample material when absorbs the X-rays, the process is called the photoelectric if emits X-rays, the process is called X-ray fluorescence. A spectrum is produced with multiple peaks showing the elemental concentrations at different positions. Materials analysed using XRF can be solid, powders (in the form of pressed pellets and fused beads) and liquids.

Solid samples: consist of metal pieces that are unprepared, samples of metal that are polished and plastics. The ideal sample for XRF analysis should have a perfect flat surface. This avoids error that result from the surface of the sample not being even, which causes the distance from the sample to the X-ray source to change.

Sample powders: Material consisting of powder that is loose is analysed by placing it into a sample cup with a support film made of plastic. This ensures a flat surface to the X-ray analyser and the sample being supported over the X-ray beam. Samples that are finely ground are more likely to be homogenous and have fewer void spaces thus providing a better analysis. By mixing the powdered samples with a binding material, they can be turned into pressed pellets or mixed with a flux to make fusion beads which provides better results.

Pressed pellets: This method of sample preparation is more rigorous than pouring loose powders into a sample cup. The process involves grinding a sample into a fine powder, mixing it with a binder and then pressing the mixture in a die at 25 to 35 tonnes of pressure applied for 1 to 2 minutes using hydraulic sample press to produce a homogeneous pressed pellet. Sufficient pressure is required to completely compress the sample such that there are no voids in the pellet.

Fused beads: This is the ideal sample preparation method for solid samples prepared as fused beads provide a nearly perfect homogeneous representation of the sample to the XRF. Fused beads are created by mixing a finely powdered (< 75 μm) sample with a flux in a sample ratio of 5:1 to 10:1 and then heated to 900 - 1000 ^oC in a platinum crucible.

Liquids: The preparation method of liquids simply involves pouring them into a sample cup made of plastic. The main point in analysing liquid samples is to choose the correct support film that provides a balance of strength and transmission capabilities. The analysis stage requires that an X-ray transparent supporting media is used.

2.2.2 X-Ray Diffraction (XRD)

X-rays are moderately short-wavelength, high-energy beams of electromagnetic radiation. The materials analysed using X-ray diffraction usually are in crystalline form. XRD is generally a quick and non-destructive technique for mineral identification with good reproducibility. The use of XRD for determining the minerals present in coals is very effective as minerals in coals have a well-defined crystal structure (Lu *et al*, 2001).

2.2.3 Petrography

Coal petrography is a microscopic technique used to determine rank of coals (degree of coalification), and amount and type of macerals in the polished specimens (Falcon and Snyman, 1986). The petrological microscope is a very vital tool in the study of coal petrography, and it remains crucial in obtaining information that relates to coal constituents and its technological response before the coal utilisation process (Hessley *et al.*, 1986). Petrographic analysis helps to know the rank of coal and the microlithotypes. To know the shape of the macerals and minerals within the coal structure.

Petrographic data is used to determine which coal constituents are the most likely to cause wear. Several publications have reported the correlations of coal petrology to its abrasiveness (Falcon and Falcon, 1987).

2.2.4 Scanning Electron Microscope

The Scanning Electron Microscope (SEM) is one of the instruments used for characterisation of mineral grains in terms of morphology (shape and size). SEM techniques can analyse the fine grains (< 10 µm) of minerals present in coals, unlike microscopes that have not been able to resolve the mineral matter in coals less than 10 microns.

Energy Dispersive X-ray Spectrometry (EDS) is attached to the SEM which allows for qualitative chemical analysis. The most significant advantage of SEM over optical microscopes and microprobes is that SEM techniques are induced by EDS, allowing qualitative chemical analysis. SEM techniques are as a result used rapidly when compared to conservative methods (Creelman and Ward, 1996).

2.2.5 Proximate Analysis

Coal analyses are often reported as ultimate and proximate analysis. The ultimate analysis is the determination of elemental concentration in the coal namely carbon, hydrogen, oxygen, nitrogen, and sulphur. The methods that are used includes the combustion method used for (carbon, hydrogen, and oxygen) analysis, the Kjeldahl's method used for nitrogen analysis and the Eschka method used for sulphur analysis. Proximate analysis is the determination of moisture content, volatile matter content, ash content and fixed carbon content. For determination of moisture content finely powdered coal is weighed in a silica crucible, and the crucible is placed in an electric hot air oven, maintained at 105 - 110 ^{o}C for an hour. The crucible is then taken out, cooled, and placed in a desiccator, and weighed for loss in weight. For determination of a volatile matter, the same crucible is covered with a lid and placed in a muffle furnace maintained at 925 ^{o}C for 7 minutes. The crucible is cooled in air and then in a desiccator and weighed again.

Proximate analysis is used for classification of coal according to rank. It helps in an understanding of the grindability and friability of coal, thus determining how comminution machinery interacts with coal and how fines are generated. Proximate analysis components are calculated using the following equations:

$$\text{Moisture (\%)} = \frac{\text{Loss in Weight}}{\text{Initial Weight of Coal Sample}} \quad (1)$$

$$\text{Volatile Matter (\%)} = \frac{\text{Loss in Weight}}{\text{Weight of Coal Sample after Moisture}} \quad (2)$$

$$\text{Ash (\%)} = \frac{\text{Weight of Ash}}{\text{Weight of Coal Sample}} \quad (3)$$

$$\text{Fixed Carbon (\%)} = 100\% - (\%\ \text{Moisture} + \%\ \text{Ash} + \%\ \text{Volatile Matter}) \quad (4)$$

$$\text{Fuel ratio} = \frac{\text{Fixed Carbon}}{\text{Volatile Matter}} \quad (5)$$

2.3 Coal Lithotypes

Lithotypes are macrostructures of coal that can be seen by the naked eye. Coals have internal layering, called banding. Coal lithotypes are based on the presence or absence of banding and the brightness or dullness of individual bands that can be seen with the naked eye. Examples of coal lithotypes include vitrain, clarain and durain as shown in Table 2.1. Coal containing durain is expected to break, generating big particles and fewer fines whereas vitrain having brittle nature leads to excess fines generation (Sykorova, 2005).

Table 2.1 Classification of Coal Lithotypes

Coal Type	Lithotype	Appearance
Humic (banded)	Vitrain	Bright, black, shiny, and brittle bands, usually with cracks or fissures. Tends to break into small cubes.
	Clarain	Semi-bright (vitrain and clarain), black, and finely interlayered.
	Durain	Dull, black to grey-black bands which have a rough surface. Bands have fewer cracks (fissures) than vitrain. Tends to break into lumps.
	Fusain	Black to grey bands with silly lustres (shine). Sometimes fibrous. Soft and friable, sometimes like charcoal.
Sapropelic (non-banded)	Cannel	Black to dark grey, non-banded coal with dull to greasy lustres (shine). Often breaks with conchoidal (glass-like) fracture.
	Bog head	Like cannel but brownish colour.

(Adopted from Suyman, 1986)

Macerals are components of coal that are microscopic and have various physical, optical, and chemical properties that make the organic fraction of coal. Macerals originate from the plant material and are classified into three groups as *vitrinite (huminite in low-rank coal), inertinite and liptinite*. This classification system has been established by the International Committee for Coal and Organic Petrology (ICCP). This classification system is modified differently across the world to show the specific characteristics of coal from different geography and stratigraphy.

The vitrinite group represents woody plant material (e.g. stems, trunks, roots, and branches) derived from lignin and cellulose of plant tissues. The liptinite group includes components that are chemically more resistant to physical and chemical degradation than other macerals such as pollen, spores, cuticles, waxes, and resins (Falcon, 1968). Liptinite macerals are enriched in hydrogen owing to a more significant number of aliphatic components. The inertinite maceral group originates from the same material as the vitrinite group and the liptinite group but has more aromatisation and condensation. Inertinite macerals have higher carbon content than vitrinite group macerals of the same rank because they were carbonised, oxidised, or subjected to chemical or bacterial attacks before coalification, usually in the peat stage.

2.4 Fines Generation

Several factors lead to fines generation along the processing route such as the cutting cycle and technique of the continuous miner, belt conveyor speeds, drop heights of the transfer points and the feeder breaker. In the following sections, the factors that result in coal degeneration are discussed in detail.

2.4.1 Abrasion and Impact

Coal grindability was defined by Robinson (2019) as the ability of coal to withstand crushing forces. Coal grindability is applied to comminution to determine the relations of coal with the machines and how this leads to fines generation. According to Sarma and Morley (2018), coal with high moisture content is easier to grind while coal with high volatile matter is hard to grind. Coal friability is a measure of coal's ability to withstand forces that cause coal to break down into smaller pieces and is a function of coal strength and rank. A sieve analysis procedure is used to assess the particle size distribution (also called gradation) of coal by allowing it to pass through a series of sieves of progressively smaller mesh sizes. The amount of coal that is collected by each sieve is then expressed as a fraction of the whole mass. This helps to determine the number of fines contained in the coal.

Dropping coal from high elevations generates more fines compared with dropping it from a lower height, as shown in Figure 2.2 (Tavares and Carvallo, 2011). According to Marcelo (2011), the transfer points also play a significant role in coal degeneration. At the same speed, more massive coal particles tend to disintegrate more than the lighter ones due to their momentum. Moreover, coal breakage and the quantity of coal lost due to shattering and falls from conveyors is a crucial consideration for coal sellers, mines, power plants, preparation plants, ports, and terminals.

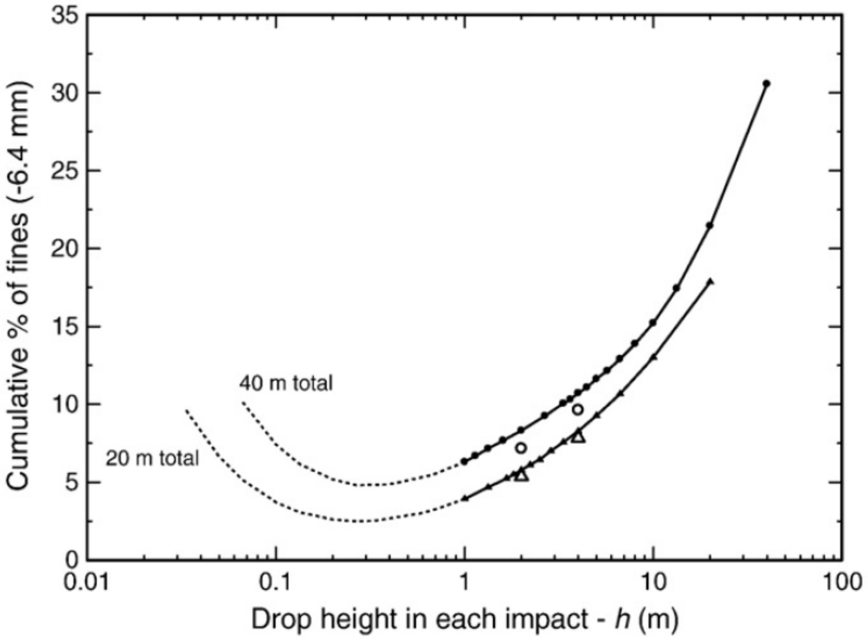

Figure 2.2 Impact of Drop Height on Fines Generation (Tavares and Carvalho, 2011)

Determination of abrasion and impact: The abrasive nature of coals is determined by calculating the abrasion index (AI) of ground coals. Abrasion index is a function of the total mass lost by the iron blades divided by the load mass of coals (Scieszka, 1985; Spero, 1990; Spero *et al.,* 1991). The abrasion of coals is studied using abrasion index tester pot following a method named Yancey, Geer and Price (YGP) as it was proposed by Yancey, Geer and Price in 1951.

The YGP method, involves introducing specific particle size coal that weighs 2 kg into a grinder that contains four blade cutting elements. The charge is ground by rotating a mill at 12000 revolutions at 1470 rpm. Ground coals are removed and put into containers after the set 12000 revolutions. The blades are weighed on a calibrated balance, from which the difference is divided by feed mass. The results are then taken as an indication of the AI of the coals.

Drop shatter test: To estimate the capacity of coal withstand breaking while being handled and transported the drop shatter test is performed. During a drop shatter test, coal of known size is dropped onto a steel plate from a specific height. The broken pieces are then sorted, and the mass of each size group is recorded. The friability of coal is represented in percentage form by the original sample that shattered into each size grouping.

Coal hardness: Various constituents of coal are known to influence the abrasive nature of coal (Spero *et al.*, 1991), which can be divided into chemical, physical, and mechanical properties. A chemical property that affects abrasiveness is moisture (Terchick *et al.*, 1963). Minera content (clays, carbonates, pyrite, and quartz), microlithotypes and macerals are an example of physical properties that affects abrasion. The hardness of coal also influences its abrasion (Scieszka, 1985; Hutchings, 2002).

Vickers hardness test: The test was developed as an alternative to the Brinell method to measure the hardness of materials. Its basic principle is to observe a material's ability to resist deformation from a standard source with an indenter when a load is applied. Vickers Hardness (HV) is the quotient obtained by dividing the load in kg by the area (in mm^2) of indentation. It can be calculated using equation (6):

$$HV = \frac{1.8544 \times F}{d^2} \tag{6}$$

where: F = Load in kg

d = Arithmetic mean of two diagonals (d_1 and d_2) of indentation in mm

2.4.2 Conveyor Belts and Transfer Points

From studies conducted on degeneration control by various authors, it has been concluded that degradation of material in transfer chutes result from the change of energy imparted to the material. This may be kinetic, impact or frictional energy. Whereby the trajectory of the payload determines the amount of degradation possible. The trajectory results from the in-bye conveyor characteristics such as speed, pulley diameter and conveyor profile.

By controlling the trajectory, degradation can also be controlled. Speeding up the conveyor belt results in discharge angles becoming relatively large, thus leading to an increase in the spread of projected material. This increases the number of fines generated. Figures 2.3 and 2.4 show the effects of conveyor belt speed and pulley speed on fines generated, respectively.

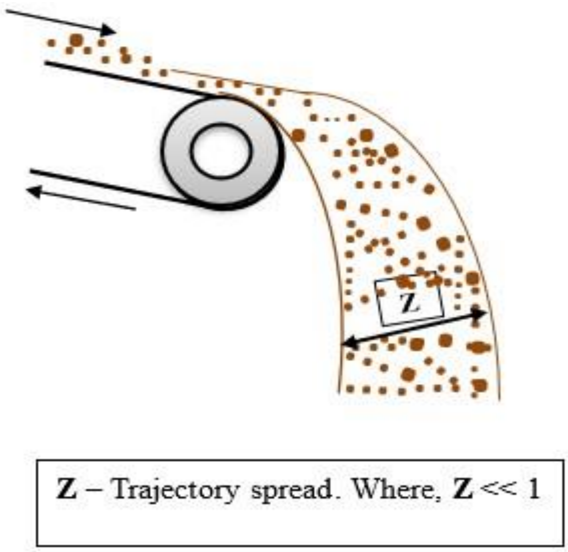

Figure 2.3 Trajectory Spread of Coal based on Conveyor Belt Speed (Goodwin, 2017)

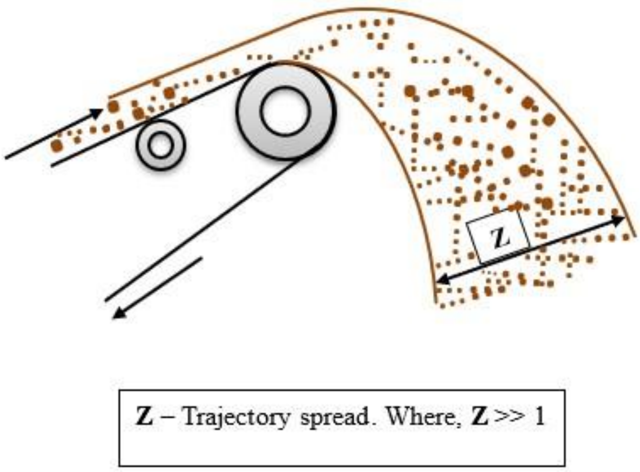

Figure 2.4 Trajectory Spread of Coal based on Pulley Speed (Goodwin, 2017)

2.4.3 Continuous Miner (CM)

The cutting efficiency of continuous miners is dependent on the drum, conditions of the cutting pick and on the operator's skill. Cutting of coal with a CM requires a high level of efficiency to minimise fines generation. Interactions between the cutter head and the coal face then become imperative. The parameters that influence cutting efficiency include rake angle, back clearance angle, angle of attack and line spacing. These are discussed in detail in the next sections.

Rake angle: This is the angle of the cutting face relative to the work. There are two types of rake angles (back-rake angle and side rake angle), both of which help to guide chip flow.

Back clearance angle: The angle between a plane passing through the cutting edge and a plane containing the end surface of a cutting tool in the direction of cutting motion. The back-clearance angle should not be less than 5° and not greater than 10°.

Angle of attack: This is the angle between the axis of the pick and the plane of the face being cut. The optimal cutting angle of soft rock is between 45° and 55°. Cutting at an angle of 55° reduces the number of fines generated more significantly than when cutting at 45°.

Line spacing: Line spacing is the distance between adjacent picks or tools in the axial direction, on the shearer drum or cutter. If the line spacing is too close, the cutting is inefficient due to the over-crushing of the rock leading to fines generation. If it is too extensive, the tool cuts in an unrelieved mode (tensile fractures from the next cut cannot reach each other to form a chip), creating a groove-deepening situation, resulting in the formation of a rib between cuts. Figure 2.5 shows how line spacing affects cutting efficiency.

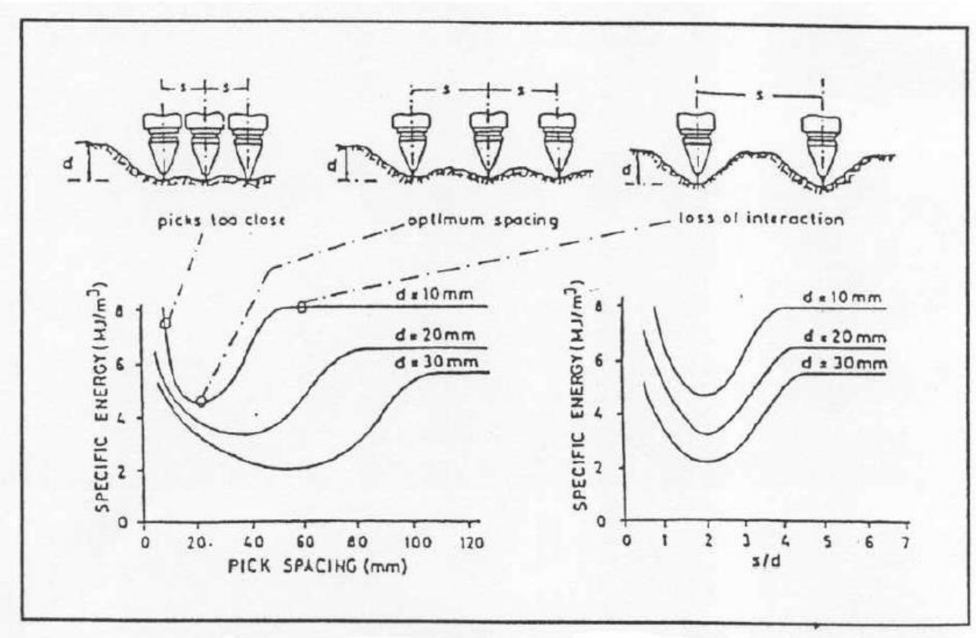

Figure 2.5 Effect of Line Spacing on Cutting Efficiency (Raghavan, 2014)

2.4.4 Feeder Breaker

A feeder breaker is an underground primary crusher for crushing coal before it is loaded into the conveyor belt. Its ratio is adjusted to match the type of coal seam to avoid over crushing in-case of “soft” coal. The time coal takes to be crushed is essential as the longer it stays in the crusher, the more fines are produced. This case is typical for old feeder breakers.

2.5 Case Study Mine

The main production operation in MCM is the mining of coal using continuous miners. The continuous miners cut and load the coal onto the shuttle cars which haul the coal to nearby feeder breakers. The feeder breakers crush the coal into suitable sizes for transportation to surface via the main conveyor belt. The conveyor belt system consists of main conveyors with a width of 1500 mm and section conveyor belts which a width of 1050 mm and 1350 mm. Section conveyors haul coal from various sections through transfer points into main conveyors which haul the coal to the run-off-mine stockpile on the surface. The speed of the conveyor belts varies from one another after the transfer chutes. Figure 2.6 shows the conveyor system at MCM.

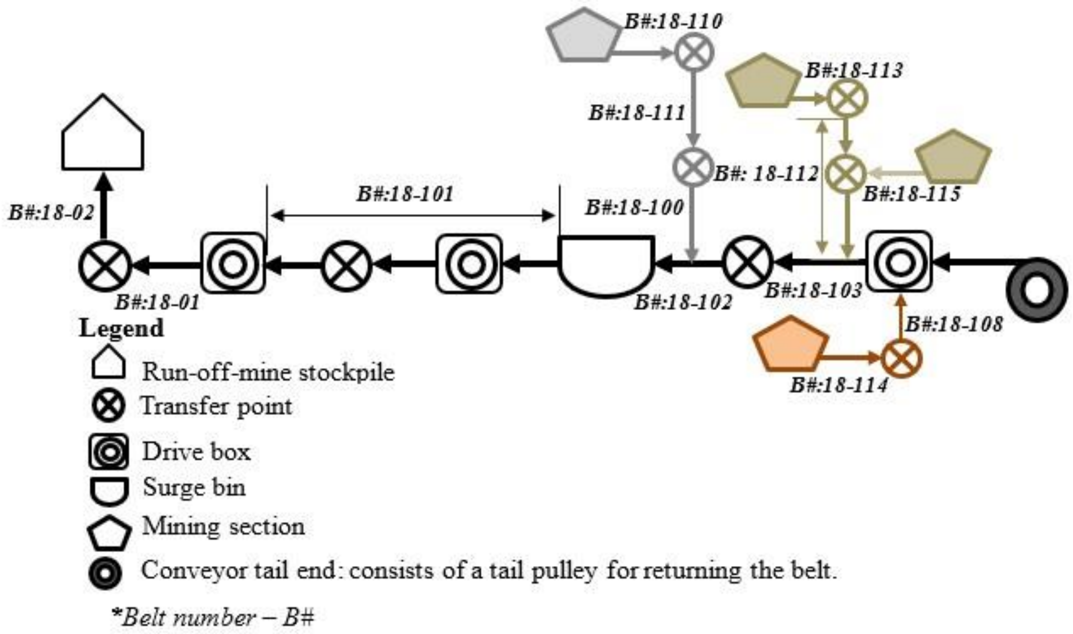

Figure 2.6 Schematic Diagram of MCM Belt Conveyor

The ventilation system used in MCM consists of two Howden axial flow fans. Each fan is 2980 mm in diameter and handles 300 m^3/s of air. The mine uses the air coursing system of ventilation in which fresh air is coursed through the intake airways and is directed towards the working face by brattices before leaving the section via two return airways as shown in Figure 2.7.

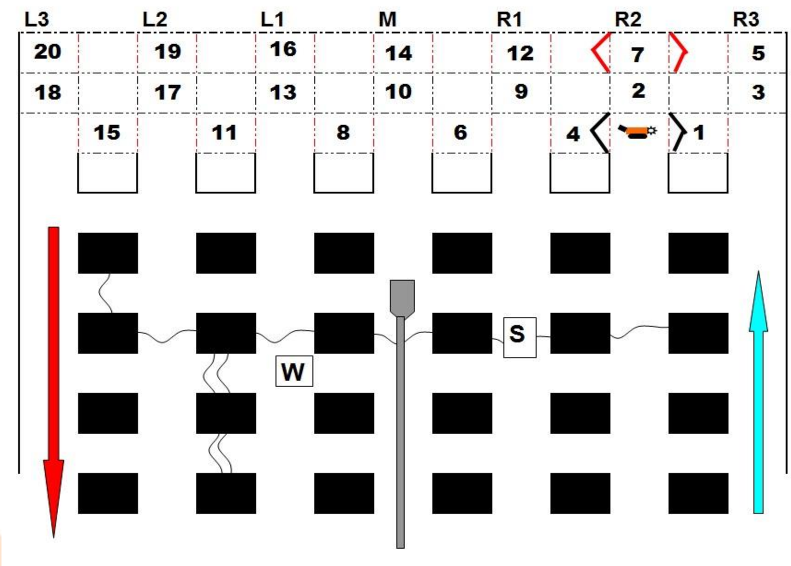

Figure 2.7 MCM Coursing Ventilation System

Coal from the Runoff Mine (ROM) stockpile as shown in Figure 2.8, goes to the primary crusher (oversize) for reduction into desirable sizes while the undersize and middlings go through screening for separation at the double-deck screen. The undersize with fines are passed on to the Coal Wash Plant while the middlings go through the secondary crusher for further crushing. These are then taken to BPC B stockpile together with coal from primary crushing that goes to BPC A stockpile.

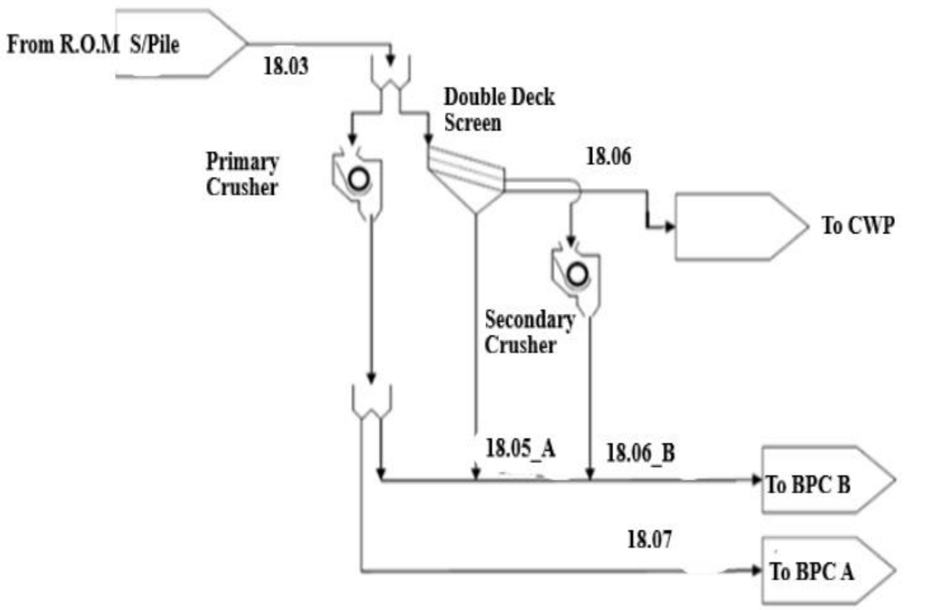

Figure 2.8 Flow Sheet of Coal Processing at MCM

The Wash Plant has a capacity of 400,000 tonnes per annum and a feed rate of 200 tph. Coal goes through screening, where it is washed with water to remove the fines. Flocculants are also used at this stage to agglomerate the unwanted particles making them drop out of solution. The coal then goes into the Dense Medium Separation drum where separation based on density takes place (overflow and underflow). The middlings are retained through magnetic separators.

2.6 Fines Generation Engineering Controls

Generation of coal dust is inevitable in coal mining, but it increases when more fines are generated. Several engineering controls are employed to reduce the dust in mining. Primary control methods used to reduce airborne dust in underground coal mines include ventilation, suppression (sprinkling with water and other chemicals) and the use of dust collectors.

2.6.1 Ventilation

The mine ventilation system uses displacement and dilution to reduce the dust concentration in the air by supplying fresh and uncontaminated air to mining faces. The dilution mechanism operates when a dust cloud surrounds workers, and additional fresh air from the ventilation system serves to reduce the dust concentration by diluting the cloud. The displacement mechanism operates when workers are upstream of dust sources, and the air velocity is high enough to keep the dust downstream reliably. The basic principle behind dilution is to provide enough fresh and uncontaminated air to dilute the dust. Often, the dust is reduced approximately in proportion to the increase in airflow, but not always. When air moves through ventilation ducts and shafts at high speed, the cost of heightened airflow and the technical barriers can be substantial (Jayaraman, 1986).

Displacement ventilation operates by confining the source of the dust and keeping it downstream away from the workers. Every mine passage or tunnel with an airflow direction that puts dust downstream of workers uses displacement ventilation. In mines, tunnel boring machines or continuous miner faces on exhaust ventilation use displacement ventilation. Enclosure or isolation of a dust source, such as a conveyor belt transfer point, along with the extraction of dusty air from the enclosure, is another example of displacement ventilation (Jayaraman, 1986).

2.6.2 Conveyor Belts and Transfer Points

Several sources within the conveyor belt can produce considerable amount of dust such as when the belt moves over the idlers and at a transfer point. Another significant source of dust within the belt is when material spills. High-velocity ventilation air assists in the release of dust by drying the material and picking up settled particulates. Methods to deal with belt dust include the proper enclosure of transfer points, spraying the material with water or another solvent to allay dust generation, avoidance of sticky substances on the carrying and return idlers, and exhausting the air inside using dust collectors (Goldbeck and Marti, 1996; Swinderman, 1997). Drop height experiments performed by Sahoo (2007) show that the tests performed in buffered material produced less fines than the ones that were not buffered. Hence the cushioning of conveying equipment produces less fines.

2.6.3 Continuous Miner

Dust control methods for continuous miners include sound water spray systems, a modified cutting cycle, operating the CM from a remote-control location, proper water filtration, and regular bit replacement.

Modified cutting cycle: With an improved cutting cycle, the continuous miner usually sumps a foot below the face of the coal then shears to the floor as opposed to the conventional method of sumping at the roof then shearing down to the floor. This is continued for at least two sump and shear sequences. The coal from the roof and remaining rock is then trimmed when the miner backs up (Jayaraman, 1986).

Remote control: Remote-controlled machines allow the operators to avoid dusty areas and remain in uncontaminated air, hence lowering their dust exposure. A downside of remote control is that it may remove the operator from a location that is protected from roof falls, such as the cab of a continuous miner. With exhaust ventilation, dust is avoided by moving away from the face and back into the intake air. With blowing ventilation that uses line brattice, dust is avoided by stepping in front of the line curtain. In either case, dust reductions of about 90% are possible. The remote control allows the operator to step back and get away from the dust cloud that surrounds the machine. Many researchers have proven the efficiency and effectiveness of remote controls (Goodman, 1999).

Good water filtration: Frequent clogging of spray nozzles is caused by dirt and dust particles in the water line. Old spray filters are normally replaced by simple non-clogging water filtration systems (Divers, 1976).

Regular bit replacement: The cutting efficiency can be improved by inspecting the cutting drum regularly and replacing missing and dull bits, thus minimising the dust generated. Work by Organiscak (1996) shows that bits designed with large carbide inserts and smooth transitions between the carbide and steel shank generally produce less dust.

2.6.4 Roof Bolter

Most dust exposure of the operators of the roof bolter is from upstream sources of dust such as the continuous miner. The region around the roof bolter is contaminated by the roof bolter during drilling and its dust collection system which permit considerable amount of dust to escape through their dust collector systems. Such contamination is possible when an insufficient amount of clean air is available to dilute the dust. When dry dust collection systems are leaking, dust emission from the blower exhaust is the most common problem. The leak can also be caused by improperly seated or damaged filters. Also, the dust collectors of most roof bolters show accumulations of dust between the blower and filters, which results from past or current filter leaks. By running the blower for several minutes or backflushing the system with compressed air the dust can be removed (Jayaraman, 1986). Roof bolters in the mine though generates dust during drilling, due to its proper dust collection system, the impact of the dust generated by the roof bolter is insignificant. Hence, it is not considered as a potential source for dust generation in the mine.

2.6.5 Feeder Breaker

The crusher is a major dust source. To reduce this dust, the crusher is usually enclosed with steel plates and strips of conveyor belts. All skirts and seals must be carefully maintained to ensure that dust stays inside the crusher enclosure. Several sprays are mounted on internal spray bars, which generally span the width of the conveyor. Recommended spray bar locations are at the mouth of the crusher, the discharge end of the crusher, and the stage loader-to-belt transfer point (Jayaraman, 1986).

2.7 Impacts of Fines Generation

Coal degradation results in coal dust that has environmental impacts such as pollution (water and air) as well as impacts on the health and safety of workers, including the mining equipment and machinery.

2.7.1 Coal Mine Dust Exposures

The most exposure to coal dust comes from the dust generated during mining. The types of coal mining operations are underground mining and surface mining, producing distinctively different exposure variables, and disease entities. Underground coal miners are at higher risk of developing Coal Workers Pneumoconiosis (CWP) than surface or strip miners because of the higher dust levels in the underground environment. In surface or strip mining, generated coal dust is diluted by outdoor air. However, rock drilling operations associated with surface mining are associated with a higher risk of developing silicosis. The Bureau of Labour Statistics estimates that there were 51,900 people employed in the coal mining industry group in 2019 in the United States (Anon., 2019). The Mine Safety and Health Administration (MSHA) coal mine respirable dust Permissible Exposure Limit (PEL) is 2 mg/m^3 coal.

In comparison, the National Institute for Occupational Safety and Health (NIOSH) has recently lowered its Recommended Exposure Limit (REL) to 1 mg/m^3. While dust levels are below 2 mg/m^3 in most coal mines, MSHA has noted occasions in which the PEL is exceeded. High dust levels occur more often with longwall mining than with conventional mining.

2.7.2 Coal Workers' Pneumoconiosis (CWP)

The first case reported on CWP was by Gregory (1960) in a British coal mine. Coal dust was initially considered innocuous, and CWP was thought to be a variant of silicosis because of similarities in chest radiographs. This theory was disproved by Collins and Gilchrist (1928). They studied the pathologic changes in the lungs coal miners exposed to coal that was silica-free and proved that workers developed pneumoconiosis despite low silica exposure. Gough *et al.* (1940) and Heppleston (1947) have confirmed these findings that showed the pulmonary histologic lesions in people working in coal mines were similar to those working in underground coal miners. CWP is now pathologically and clinically distinguished from silicosis. The spectrum of lung lesions in coal workers is broad, and

CWP is categorised according to the severity of the disease. Simple CWP is characterised by the formation of black coal dust macules centred around the respiratory bronchioles, mainly in the upper lobes of the lung (Taylor, 1978).

2.7.3 Silicosis in Coal Workers

Silicosis is generally found in conjunction with simple CWP and is seldom an isolated form of pneumoconiosis. Microscopically, silicosis nodules appear with the typical concentric laminations of mature collagen surrounding a hyalinised and partially necrotic or calcified centre. The nodule is surrounded by a pigmented zone often containing histiocytes in reticulin stroma. Nodules are found more repeatedly in the upper lung zones but are also found in sub-pleural and peribronchiolar locations. Polarised light microscopy may reveal numerous weekly birefringent particles within the nodules and highly birefringent particles in the outer mantle. With chronic exposure to silica, profusion and confluence of lesions may occur, resulting in the development of conglomerate silicosis. The frequency of silicosis in coal miners can be determined only in autopsy studies due to the inability of chest radiography to distinguish between CWP and silicosis. Moreover, eggshell calcification indicative of silicosis in radiographs is often not associated with parenchymal silicosis in autopsy studies (Vallyathan, 1985).

2.7.4 Lung Cancer in Coal Miners

Compared to the general population lung cancer in coal miners occurs less frequent after adjustment for smoking and age Meijers *et al.* (1991). Epidemiologic studies on coal miners in the United States of America and United Kingdom showed a low risk of cancer of the lung for miners of coal as opposed to the general population, and mining tenure had no significant impact on lung tumours prevalence (Vallyathan, 1985). Studies from histopathology showed that lung cancer in the general population that smokes was similar to that of coal miners, with no apparent cellular differences.

2.7.5 Socio-Economic Factors

The water environment is affected by coal mining primarily by causing a drop in the groundwater table, causing water pollution or loss of water, and by changing watercourses. The water environment is affected by mine subsidence and mine drainage because water bodies that are underground are connected to the mined space through overburden that is fractured (Wu *et al.*, 2002).

The environment is significantly affected by mining wastes in the following ways: erosion and slope failure; potential leaching of contaminants into groundwater; occupation of lands; dust pollution driven by wind; air pollution and explosion by spontaneous combustion; landscape and visual; and land-use constraints. Oxidation of pyrite within spoil-heap waste pollutes the air as well as groundwater. This oxidation is controlled by access to oxygen, which in turn depends on the particle size distribution, the degree of compaction and the amount of water saturation (Bell *et al.*, 2001). The impact of mining waste can have perpetual environmental and socio-economic consequences and be extremely challenging and costly to address through remedial measures. According to Bian (2010), waste from coal mining must be managed appropriately to ensure the long-term stability of disposal facilities and to minimise or prevent any soil and water pollution from acidic or alkaline drainage and leaching of heavy metals.

Also, air pollution from coal mines is mainly due to the fugitive emission of particulate matter and gases, including explosive and noxious gases like methane, oxides of nitrogen and sulphur dioxide. Surface mining operations like drilling, blasting, handling of coal, movement of heavy machinery on haul roads, screening, sizing, and segregation units are the primary sources of such emissions. Underground mining also produces dust from uncovered coal stockpiles, and wastes dump (Bian, 2010).

Engineering control costs: Fines generation leads to more coal dust. Accordingly, the mine has to employ several engineering controls to deal with the coal dust. Table 2.2 summarises the typical engineering controls used to reduce coal dust and their cost. These methods are employed intensively when more fines are generated, leading to more losses.

Table 2.2 Dust Control Methods

Dust Control Method	**Effectiveness**	**Cost and Drawbacks**
Dilution ventilation	Moderate	High - more air may not be feasible
Displacement ventilation	Moderate to high	Moderate - can be difficult to implement well
Wetting by sprays	Moderate	Low - too much water can be a problem
Airborne capture by sprays	Low	Low - too much water can be a problem
Airborne capture by high-pressure sprays	Moderate	Moderate - can only be used in enclosed spaces

Foam	Moderate	High
Wetting agents	Zero to low	Moderate
Dust collectors	Moderate to high	Moderate to high-possible noise problems
Reducing generated dust	Low to moderate	Moderate
Enclosure with sprays	Low to moderate	Moderate
Dust avoidance	Moderate	Low to moderate

Legend: Effectiveness: Low = 10 - 30%; Moderate = 31 - 50% and High = 51 - 75%

(Source: Kissell, 1992)

Processing costs are also incurred because fines entering the Dense Medium Separator remain in suspension throughout the medium and interfere with settling rates of sinks in the drum making the sinks-floats process economically slow (Gabaman, 2016). Washing away of coal fines and coal dewatering add more costs to coal processing.

Environmental Impact Assessment (EIA) of coal is done using different impact identification tools such as checklists, networks, overlays and geographic information systems, matrices, expert systems, and professional judgement. The aim of impact identification is to take account of all the important environmental impacts and their interactions thus making sure that significant cumulative and indirect effects are not overlooked. The impact identification tools are discussed in detail in the following sections.

Checklists: These highlight the environmental factors that need to be addressed when identifying the potential impacts of a project and its activities. They differ in purpose and complexity from a simple checklist to a complex system that assigns significance by weighting and scaling the impacts (e.g. the Battelle Environmental Evaluation System, BEES). With experience, both simple and descriptive checklists can be adapted and improved to suit local conditions. Checklists provide an organised way of identifying impacts. They also have been refined for application to specific projects and categories of impacts (such as road building and dams). When proponents specialise in one particular area of development sectoral checklists are often useful. Nevertheless, checklists are not as effective in identifying inter-relationships between impacts or higher order impacts (Porter, 1998).

Matrices: A matrix is a grid-like table is used to identify the relationship between project activities, shown along one axis, and environmental features, which are shown along the other axis. Using the table, activity and environment interactions can be filled in the appropriate cells or intersecting points in the grid. Entries are made in the cells to display the severity of the impact or other features such as:

- Numbers and range of dot sizes to indicate scale.
- Symbols or ticks to identify impact type (e.g. direct, indirect, and cumulative) pictorially.
- Descriptive comments can be made.

One common method under matrices is the Leopold matrix used mostly for displaying environmental impact results. The Leopold matrix is a qualitative environmental impact assessment tool which was introduced in 1971. It is used to identify the potential impact that the project has on the environment. The system is made up of a matrix with rows representing the different activities of the project, and columns representing different environmental factors under consideration. The intersections are filled in to show the magnitude (from -10 to +10) and the importance (from 1 to 10) of the impact of each activity on each environmental component (Petts, 1999).

The Leopold matrix process is completed as follows:

1. For all the interactions considered significant mark the corresponding boxes in the matrix with a diagonal line.
2. Evaluate each box by applying a number from 1 to 10 (1 is minimum and 10 the maximum) to show the magnitude of the interaction. This number is transferred to the upper left-hand corner.
3. Mark (from 1 to 10), in the lower right-hand corner, the real importance of the phenomenon for the given activity. This provides an evaluation of the extent of the environmental impact.

Impact significance: Equation (7) is used in calculating impact significance:

$$\text{Impact Significance} = \text{Magnitude} \times \text{Value} \tag{7}$$

Networks: Networks demonstrate the cause-effect interaction of project activities and environmental characteristics. They are mostly useful in identifying and depicting secondary impacts such as indirect and cumulative impacts. Simplified networks, used in connection with other methods, help to ensure that vital second-order impacts are not overlooked in the investigation. More detailed networks are time consuming, visually complicated, and complex to produce without the use of a computer programme for the task. Nevertheless, they are a powerful aid for establishing impact hypotheses and other structured mathematical-based approaches to EIA (Petts, 1999).

Overlays and geographic information systems: Overlays are used for mapping impacts spatially and display them pictorially. McHarg (2001) popularised the original overlay technique, which is an environmental suitability analysis on which data on ecological values, topographic features and resource constraints are mapped onto individual transparencies and then summed into a composite representation of possible impacts. This approach is used in routing linear developments to avoid areas that are environmentally sensitive, for comparing site and planning alternatives, and for habitat and landscape zoning at the regional level. The downside to this approach is the lack of accuracy in differentiating the magnitude and likelihood of impacts and relating them to project actions. Moreover, the overlay process can become cumbersome in its original form.

Computer-based geographical information system (GIS) is a modern version of the overlay method. In simpler terms, a GIS stores, retrieves, manipulates, and displays environmental data in a spatial format. A set of overlays or maps of a particular area provides various types of information and scales of resolution. The application of GIS for EIA purposes is not as widespread as generally imagined.

The main disadvantages of GIS are the expense of creating a usable system and the lack of appropriate data. Nevertheless, the potential application of GIS to EIA is appreciated widely and its use is expected to increase in the future, specifically to address cumulative effects (Porter, 1998).

Expert systems: Expert or knowledge-based systems are used in problem solving, decision making and to assist diagnosis. Several computerised systems have been developed for application in EIA, mainly at the early stages of the process. For example, using a number of rules and data system screening and scoping procedures have been automated, which encode expert knowledge and judgement. A series of systematically developed questions have to be answered by the user to identify impacts and determine their significance and mitigations. Depending on the answer given to each question, the expert system progresses to the next appropriate question.

Similar to GIS systems, expert systems are a high-investment and information-intensive, method of analysis. As result, they are limited in their current use and application, particularly in many developing countries. However, they also have the likelihood to be a powerful aid to systematic EIA in the future mainly because they can provide an effective means of impact identification. By building experience over time expert systems can also be updated (Porter, 1998).

Professional judgement: Although not necessarily a formal method, professional judgement or expert opinion is commonly used in EIA. Knowledge and expertise gained in EIA work overtime can be used to systematically develop technical manuals, data banks and expert systems which assist in future projects. The successful application of the other formal methods of impact identification depends on professional experience and judgement. Expert opinion and professional judgement can be enhanced by the use of interactive methods such as science workshops and Delphi Techniques (DT), to identify impacts, model cause-effect relationships and build impact hypotheses (Sadar, 1995). The main advantages and disadvantages of these methods are summarised in Table 2.3.

Table 2.3 Advantages and Disadvantages of Impact Identification Methods

Methods	Advantages	Disadvantages
Checklists	• easy to understand and use. • good for site selection and priority setting. • simple ranking and weighting	• do not distinguish between direct and indirect impacts. • do not link action and impact. • the process of incorporating values can be controversial
Matrices	• link action to impact. • good method for displaying EIA results	• difficult to distinguish direct and indirect impacts. • have potential for double counting of impacts

Networks	• link action to impact. • useful in simplified form for checking for second order impacts. • handles direct and indirect impacts	• can become very complex if used beyond simplified version
Overlays	• easy to understand. • locus and display spatial impacts. • good siting tool	• can be cumbersome. • poorly suited to address impact duration or probability
GIS and computer expert systems	• excellent for impact identification and spatial analysis • good for experimenting	• heavy reliance on knowledge and data • often complex and expensive

(Source: Petts, 1999)

2.7.6 Impacts of Coal Dust on Soil and Vegetation

The impacts of coal dust on soil and vegetation are discussed in the next sections.

Soil: During stockpiling fine coal dust particles are airborne and affects a large area of the mine. This dust ends up settling on the soil and affect the quality of the soil. As coal dust from the mine settles on the soil and accumulates over time, it ends up affecting the pH of the soil.

The pH of the soil affects the amount of chemicals and nutrients that are soluble in soil water, and consequently, the amount of nutrients available to plants. Most mineral nutrients are readily available to plants when the pH of the soil is near neutral. The development of strongly acidic soils (pH < 5.5) can result in poor or stunted plant growth.

Vegetation: Stockpiling of coal also has a significant impact on vegetation since this activity is done in the open atmosphere and affect larger areas around the mine. When dust settles on the leaves and branches of plants, it causes many adverse effects on the morphology and physiology of the plants. Dust deposition on the leaves decreases productivity (e.g. chloroplast content and stomatal blockage). Hence, it affects the colour of the leaves.

2.7.7 Trace Elements in Soil and Water

Pollution of mining areas due to trace elements is a significant challenge of the environment for the mining industry globally. Coal mine slag that finds its way into streams results in a certain amount of trace elements entering the soil, water, and surrounding environment.

Pollution hazards of some trace metal elements such as cadmium (Cd), zinc (Zn), mercury (Hg) and lead could be acute due to the degree of toxicity they present even in low concentrations (Carvalho *et al*., 2011). Their long-term accumulation poses a severe threat to human health. Understanding the sources and relevant characteristics of trace metals provides useful information for policymakers to effectively develop mine remediation policies.

For analysing trace elements found in soil and water several methods are employed including, Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES), Inductively Coupled Plasma-Mass Spectroscopy (ICPMS) and X-Ray Fluorescence (Bhuiyan *et al*., 2010).

2.7.8 Solution to Coal Mine Environmental Issues

The core ways of solving environmental problems in mining can be categorised into two types. First, is the taking of measures to reduce the impact of mining on the environment during mining. The other is steps taken to mitigate the environmental impact after mining, as illustrated in Figure 2.9.

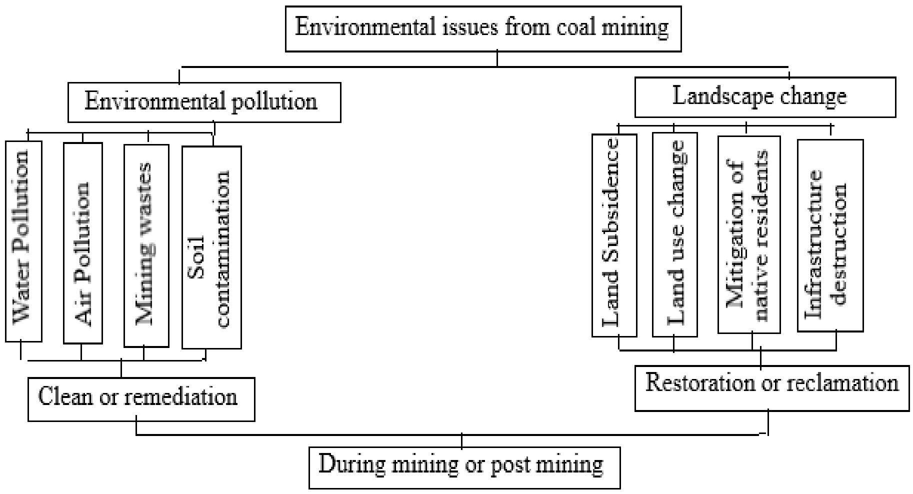

Figure 2.9 Conceptual Framework for Solving Coal Mine's Environmental Issues (Wu *et al*., 2002)

Green mining, as proposed by Qian (2003), is one of the many ideas suggested to solve environmental problems. The basic principle of these ideas is the distribution behaviour of joints, fractures and bed separations and the seepage flow of methane and water through broken rock strata caused by mining. Green mining techniques under development include water-preserved-mining, grouting into the space between separated rock layers to reduce surface subsidence and coal mining under surface infrastructures. Other methods include backfill mining and partial extraction, simultaneous extraction of coal and coal-bed methane, underground coal gasification, underground discharge of partial mining wastes and roadway support that is underground.

A series of accidents in mines from the past years has proved the importance of reusing wastes from the mine and the necessity to improve procedures in waste management. Management of mining wastes include their reduction, recycle and reuse. This method is also referred to as cleaner production, clean technology, waste minimisation, pollution prevention, waste recycling, resource utilisation and residue utilisation. In order to reduce production of mining waste innovative mining techniques are the primary ways.

A trial was carried out to minimise waste from mining on surface by backfilling the stopes with mining wastes formed after robbing the coal pillars at the Xingtai Coal Mine in Hebei Province, China. Xinwen Coal Mining Company in Shandong Province operating the Suncun Coal Mine, backfilled the mined stopes by crushing waste from mining and mixing it with cement to minimise subsidence of the ground. It was verified that the production of coal mining waste could be decreased by 10% using these new innovative methods. Mining wastes are also widely used as raw materials for making bricks (such as coal fines), fuel for power plants and other infrastructural materials such as paving, dam or landfill that is subsided.

Sustainable development can be achieved by recycling mining waste. Zero waste target is challenging to accomplish, for example, burning of waste that contains coal to produce electricity. Still, then more than 80% of waste containing coal ends up as fly ash, boiler slag or bottom ash in the combustion residues, which must be subsequently used for other purposes (Dharmappa *et al*., 2000; Bian *et al*., 2010).

CHAPTER 3

METHODOLOGY

3 INTRODUCTION

The experiments discussed in this work were performed using coal from MCM. Four samples, weighing 20 kg each, were obtained from the four sections. The sections are South Main 3/1, SM4/8, SM 4/5, and East Main 1/1, seven tests, i.e., sieve analyses, drop shatter test, lithotype examination, proximate analyses, Vickers hardness test were conducted using these samples. Also, eight samples, each 20 kg were collected, four from transfer points, three from conveyor belts and one from the run-off-mine (ROM) stockpile. Out of 4 from transfer points, two samples (HTP1 from belt 18-114, HTP2 from belt 18-102) were collected before the transfer point while two samples (LTP1 from belt 18-108, LTP2 from belt 18-101) after the transfer points. Out of three from conveyor belts, CB1 was collected from 18-114 close to HTP1 sample, CB2 from 18-113, and CB3 from 18-102 close to HTP2 sample) (see Appendices 3 and 4). These were placed into correctly labelled sample bags because of the different experimental and procedural requirements. Since, coal is composed of organic and inorganic matter, various experiments had to be conducted to find the chemical and physical characteristics of coal that lead to its disintegration into fines. All the samples were exposed to sieve analysis to obtain different size fractions. Other types of data like, mineral data and chemical data (major oxide data) are secondary data taken from company reports. The major oxide data is produced using Energy Dispersive System (EDS) and mineral data is produced using petrological microscope. Procedures for sampling on conveyors and at the stockpiles are described in Appendices 1 and 2 respectively. Appendices 3 and 4 show the sample description and sampling location respectively.

3.1 Sieve Analysis

Coal samples from the four mining sections were screened for 40 minutes and various size fractions recorded. Sieves used were 3.35 mm, 6.3 mm, 8 mm, 12.5 mm, 25 mm, 37.5 mm, 45 mm, 53 mm, 63 mm, 75 mm and 90 mm. The number of fines (<3.35 mm) produced was then expressed as a percentage of the total sample mass to determine their quantity in each section.

3.1.1 Drop Shatter Test

The following sieves were used to screen coal of various sizes: 6.30 mm, 8.0 mm, 12.5 mm, 25 mm, 37.5 mm, and 45 mm. The mass of each size fraction was recorded. A container lined with a steel plate was used in the experiment. Coal was dropped three times from a height of 2 m to allow each coal particle to be subjected to impact when hitting the steel plate. The crushed coal was then screened, and its mass was recorded. Data from the particle size distribution was then used to determine the friability of coal from four mine sections. Four samples of coal from the four mining sections were used for the test.

3.1.2 Lithotype Examination

Distinguishing the lithotypes and the thickness of bands in the samples of coal taken from four sections enables a comparison of the differences in the coal of the four sections and the type of coal they possess. In this examination, the coal samples of size ranging from 50 mm to 80 mm were used.

3.1.3 Proximate Analysis

Determination of moisture content, volatile matter content, ash content, fixed carbon content was carried out at chemical engineering laboratory, BIUST using muffle furnace. The procedure for proximate analysis of coal is described in Appendix 5.

3.1.4 Vickers Hardness Test

Coal samples of dimensions (4 cm × 2.3 cm × 3 cm) were cut and polished to obtain smooth surfaces. Four samples were prepared for each section. After placing the sample on a stage using 10X magnification, an area was identified where an indentation was made with a 5 kg load. The load was maintained for 12 seconds to test for the hardness of the coal. After load removal, the dimensions of the indentation were measured, and the hardness was calculated.

3.2 Feeder Breaker

The conditions of the feeder breaker in each section were assessed, and the Particle Size Distribution (PSD) of coal from each feeder breaker was analysed to determine their impact on the generation of fines.

3.3 Conveyor Belt Speeds

Various belt speeds for main conveyor belts and section belts were obtained to investigate their effects on fines generation. Information on the height of the transfer points was also considered as they play a role in fines generation.

3.4 Cutting of the Continuous Miner

The cutting action and cycle of the continuous miner were observed on several occasions to determine its effects on fines generation. Information on the operator's skill, conditions of the drum and cutting picks (angle of attack and line spacing) were also considered.

3.5 Sensitivity Analysis

The relative influence of feeder breakers, belt speeds and transfer points on fines generation at the run-off-mine (ROM) stockpile based on particle size distribution is evaluated by the cosine amplitude method (CAM; Yang and Zhang, 1997). This method is used to obtain similarity relations between the involved parameters. To apply this method, all of the data pairs were expressed in common X-space. The data pairs used to construct a data array X defined by equation (8) and (9):

$$X = \{x_1, x_2, x_3, \ldots x_i, \ldots., x_n\} \tag{8}$$

Each of the elements, X_i, in the data array X is a vector of lengths of $\boldsymbol{m}$, that is:

$$x_i = \{x_{i1}, x_{i2}, x_{i3}, \ldots, x_{im}\} \tag{9}$$

Thus, each of the dataset can be thought of as a point in m-dimensional space, where each point requires m- coordinates for a full description. Each point in space has relation with results in a pairwise comparison. The strength of the relation between the dataset, x_i and x_j is given by equation (10):

$$r_{ij} = \frac{\sum_{k=1}^{m} XikXjk}{\sqrt{\sum_{k=1}^{m} X^2ik \sum_{k=1}^{m} X^2jk}} \tag{10}$$

where: i, j and k are coordinates in a three-dimensional space.

3.6 Impacts of Fines on Production

The wash plant's production losses were determined through an examination of missed deadlines, stoppages due to tail end blockage, and conveyor belt breakdown.

Environmental considerations: A Leopold matrix was used as an impact identification tool to determine the activities linked to fine coal generation that is supposed to have an impact on workers, the environment and the existing social conditions that could be affected by the fines. An assessment of the environmental impact of dust generation was done. This included evaluating the impact of dust generation on the health and safety workers and equipment.

CHAPTER 4

DATA COLLECTION AND ANALYSIS

4.1 Sieve Analysis

Figure 4.1 shows that coal from SM 3/1 produces more fines (12.65%) than the coal from the other three sections. This is supported by results from the drop shatter tests which show that coal from SM 3/1 is the most friable (31.25%) of all. South Main 4/5 (SM 4/5) coal produces the least fines among the four sections with 2.81%. This is supported by the fact that it is the least friable from the drop shatter test.

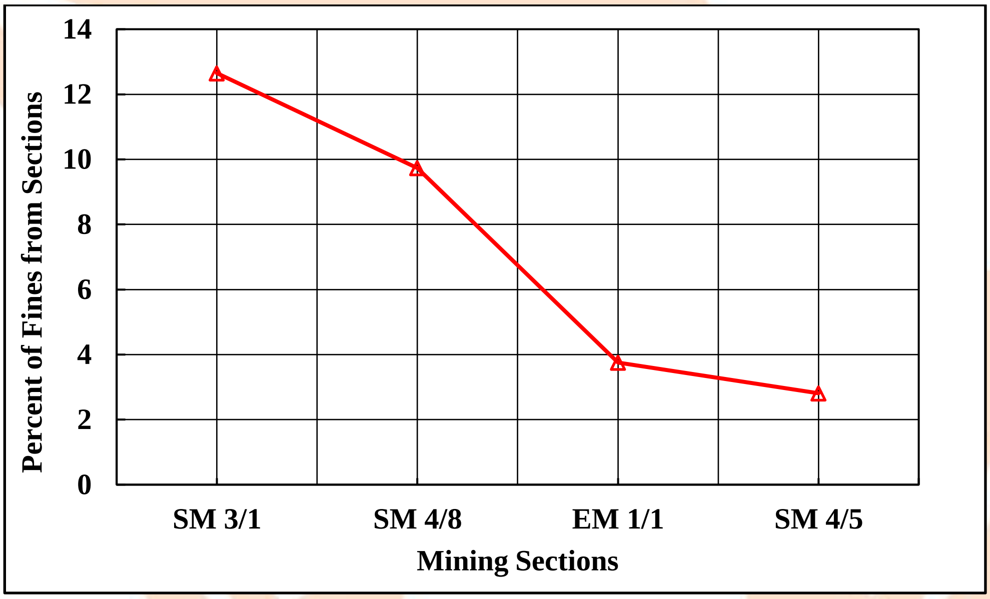

Figure 4.1 Fine Coal from Mining Sections

Feeder breakers: East Main 1/1 (EM 1/1) has a relatively older feeder breaker compared to other sections. Theoretically, older feeder breakers crush coals at slower rates leading to more fines. However, Figure 4.2 shows that the newer feeder breakers at SM 3/1 and South Main (SM 4/8) produced more fines than EM 1/1. All feeder breakers generate fines less than the specifications provided by JOY UFB (Underground Feeder Breakers) of 10% for a ratio of 2:5. Therefore, the feeder breakers at MCM do not play a significant role in fines generation.

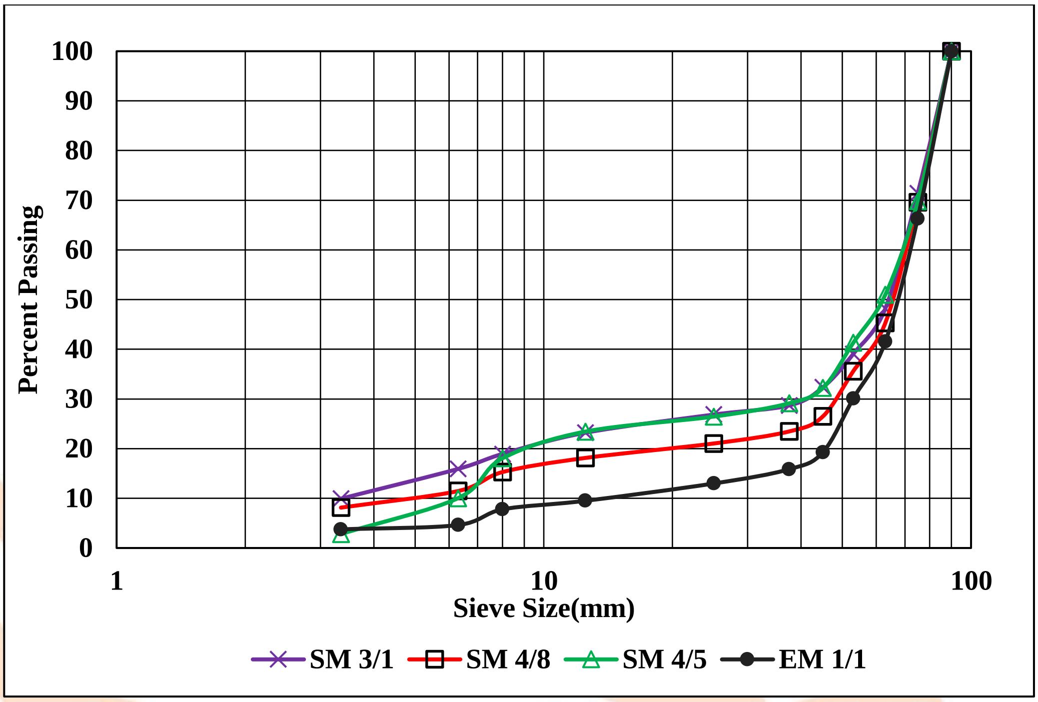

Figure 4.2 Particle Size Distribution of Coal from Feeder Breakers

Lithotype examination: It was observed that SM 4/5 coal possesses little vitrain bands and dominated by durain compared to other sections. Since durain is tough, the coal containing high content of durain is expected to break producing big particles and less fines as summarised in Table 2.1. Vitrain being insignificant, it is not expected to produce more fines even though it is brittle. This is well reflected by the drop shatter test data (Figure 4.1) where coal is least friable with low fines generation from SM 4/5 compared to other sections.

SM 3/1, SM 4/8, and EM 1/1 coal is dominant in vitrain compared to the coal from SM 4/5. SM 3/1 coal has more vitrain bands than others (Table 2.1) break into small cubes and contribute to excess fines generation. Drop shatter test data clearly indicates higher friability and in turn higher amounts of fines generation (Figure 4.1).

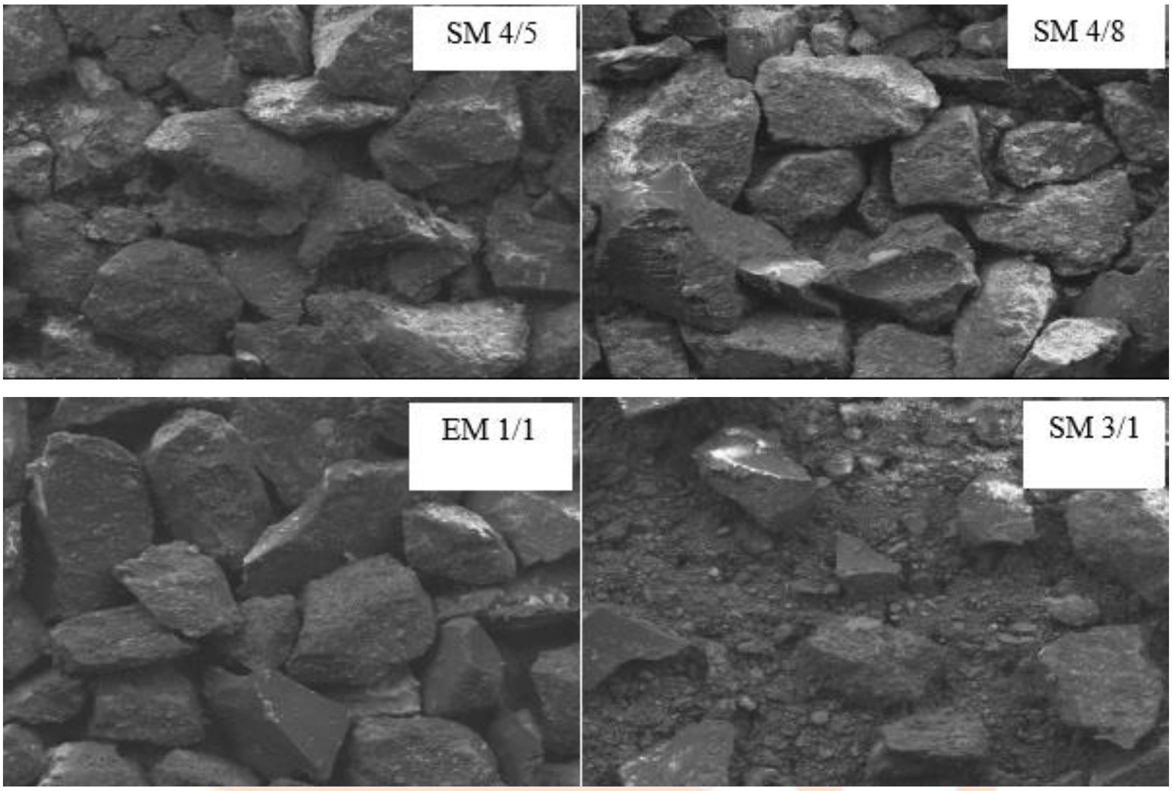

Figure 4.3 Coal Images from Different Sections, Morupule Mine

Drop shatter test: Figure 4.4 shows that the SM 3/1 coal had 7.5% of particles passing 3.35 mm before shatter test. After the coal was dropped from a height of 1.8 m, 38.75% of the coal particles were passing 3.35 mm which means the coal had a friability of 31.25% (i.e. by taking the difference of the two values). Compared to the coal from other sections, the SM 3/1 coal is more friable and is supported by the fact that the coal from SM 3/1 has more vitrain bands than the coal from the other three sections. This means it is likely to produce more fines than the coal from other sections. It also shows that for all sieve sizes the particle sizes of coal after the test reduced tremendously.

From the remaining mining sections in general coal breaks to yield medium to large particles with some of fines (< 3.35 mm) ranging from 15.5 to 18%. SM 4/5 coal is the least friable (15.5%). This is consistent with the lithotype examination results as it has more durain compared to coal from the other sections. Since durain is tough, coal containing high amounts of durain is expected to break into large particles and less fines, according to Suyman (1986).

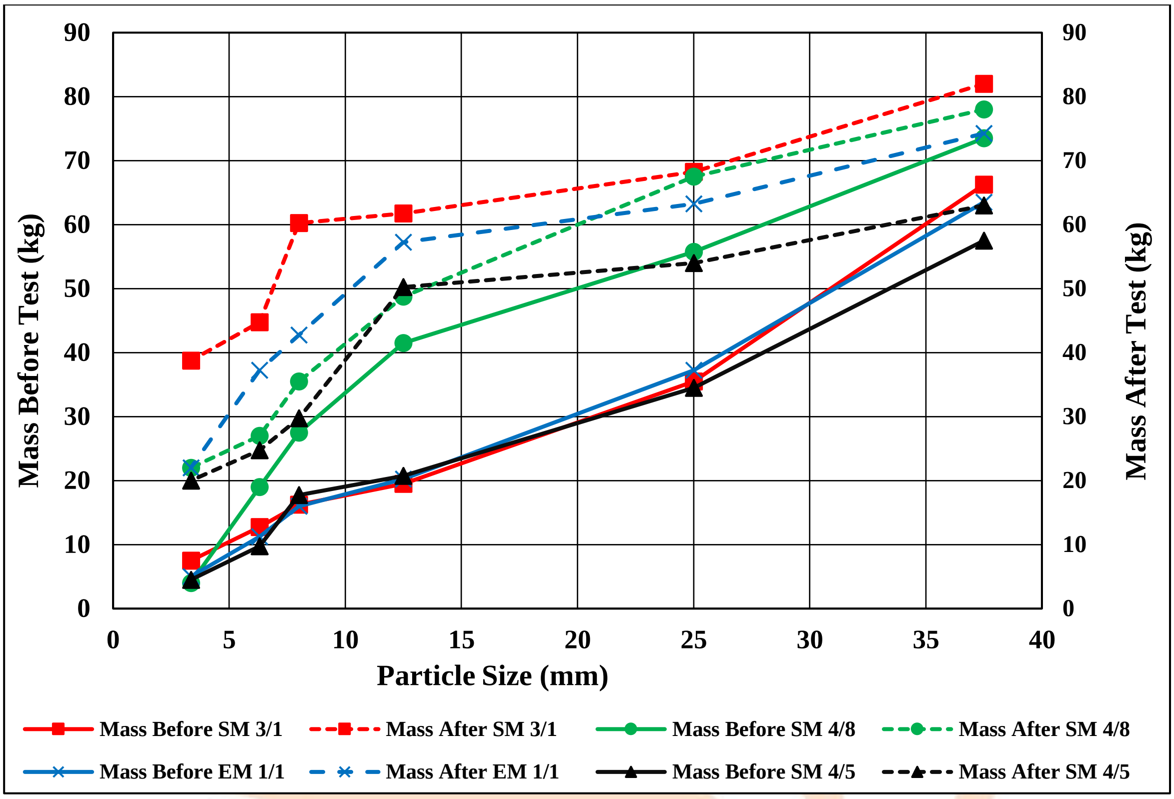

Figure 4.4 Coal Friability from Mining Sections

4.2 Particle Size Distribution of Coal

Particle Size Distribution (PSD) of coal on conveyor belts moving at different speeds and transfer points was analysed to determine its impact on the generation of fines. Four samples, 20 kg each were collected from transfer points. Two samples HTP1 (belt 18-114) and HTP2 (belt 18-102) were collected before the transfer point while two samples LTP1 (belt 18-108) and LTP2 (belt 18-101) were collected after the transfer points.

4.2.1 Particle Size Distribution at Transfer Points

Figure 4.5 shows that the belt 18-108 is generating 4% of fines while 18-114 is generating 3% fines. The difference in the amount of fines produced is due to slow moving belts (Table 4.2) and lower height (0.9 m) of the latter transfer point. Therefore, the impact and abrasion forces at that point are not significant. There is not much difference in the particle size distribution of fines for the two belts.

Figure 4.6 shows that there is an overall increase of 9% in fines generation at the surge bin, and there is a vast difference in the particle size distribution of fines before (HTP2) and after the surge bin (LTP2). Therefore, the surge bin plays a significant role in the production of fines. This is because the surge bin has the highest transfer point and the fastest belt speed of 5.5 m/s, feeding it at the mine. Therefore, with the high belt speed and high drop height (1.8 m), the impact and abrasion are increased, leading to the generation of more fines. This is consistent with experiments performed by Tavares and Carvallo (2011) by dropping coal from different heights leading to more fines generated from the higher drop heights.

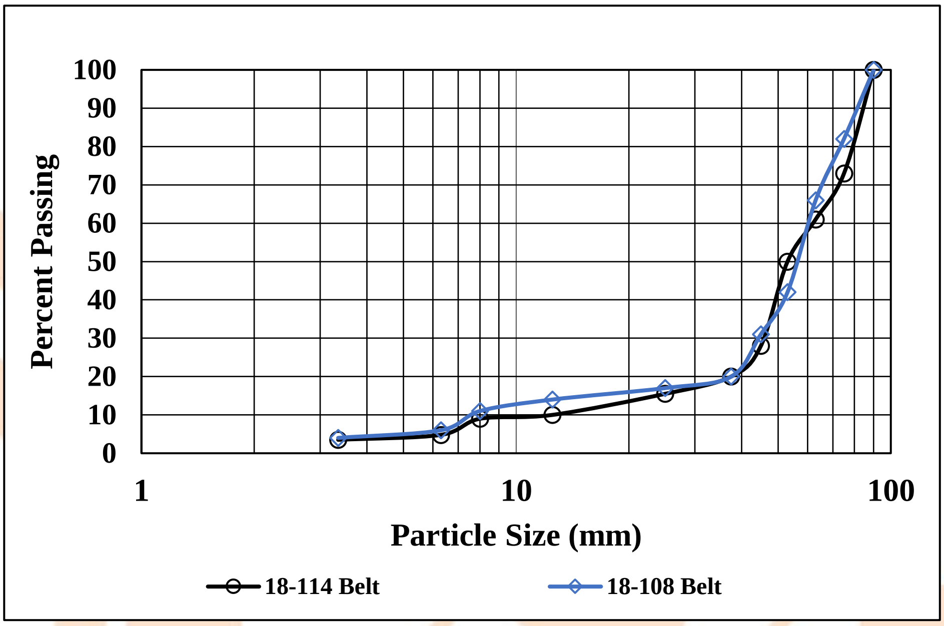

Figure 4.5 Particle Size Distribution at Transfer Point, Conveyor Belts 18-114 (Higher Side) and 18-108 (Lower Side), Height Difference is 0.9 m

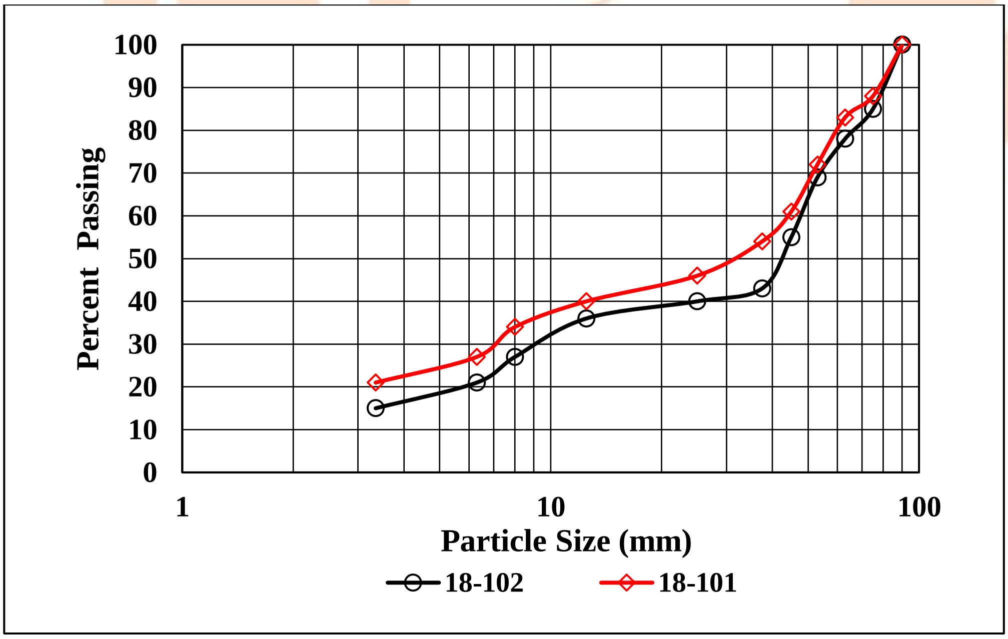

Figure 4.6 Particle Size Distribution at Transfer Point, Conveyor belts 18-102 (Higher Side) and 18-101 (Lower Side) Height Difference is 1.8 m

4.2.2 Particle Size Distribution vs Belt Speed

Table 4.1 summarises the speeds of the various belts at MCM. The results show that the belt speeds of 6 of the belts exceed 4.60 m/s (see Appendix 6 for the details).

Table 4.1 MCM Conveyor Belt Speed

Belt Number	Speed (m/s)
18-02	4.92
18-01	4.91
18-101	4.27
18-102	5.5
18-100	4.12
18-111	2.71
18-110	4.68
18-103	4.33
18-112	4.48
18-113	4.20
18-115	5.13
18-108	4.85
18-114	2.28

Figure 4.7 is a graph of PSD of fines generated on three samples from three conveyor belts (CB1 from 18-114 which was obtained near HTP1 sample, CB2 from 18-113, and CB3 from 18-102 which was obtained near the HTP2 sample). From Figure 4.7, the fastest conveyor (18-102) with a speed of 5.5 m/s produces more fines (< 3.35 mm) than the medium speed belt (18-113) and slowest belt (18-114). The results are consistent with experiments conducted by Hastie (2007) which showed that conveyor belt speeds greater than 4.60 m/s produce more fines than those at lower speeds (< 4.60 m/s). With increase in speed the abrasion between particles of coal being conveyed increases resulting in more fines generation while less speed means the friction between particles reduces thus producing less fines. Generally, the main conveyor belts in the mine have a width of 1500 mm and a higher speed than section conveyor belts (for hauling coal from mining sections and loading it onto main conveyors through transfer chutes) with a width of 1050 mm and 1350 mm, the

conveyor belt width does not contribute to fines generation. The speed of the conveyors varies after the transfer chutes.

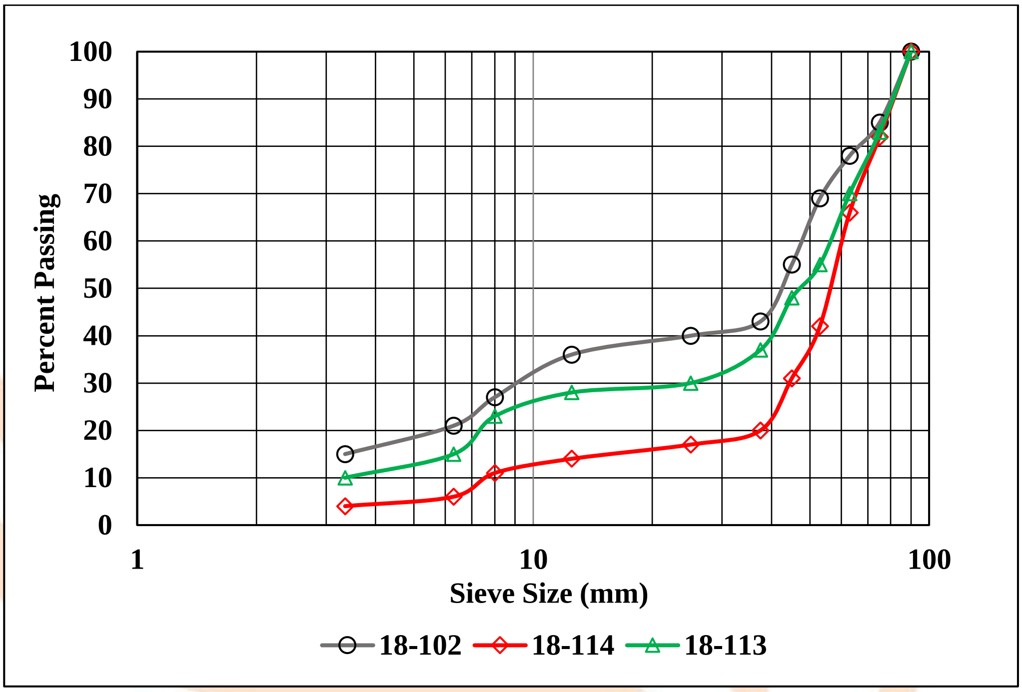

Figure 4.7 PSD of Three Conveyor Belts

Proximate analysis: Using equations (1) to (5), sample calculations were done on the coal samples from the four sections and the results are summarised in Table 4.2.

Table 4.2 Proximate Analysis Results for MCM Coal

Sample ID	**SM 3/1**	**SM 4/8**	**EM 1/1**	**SM 4/5**
Loss in Weight (g)	0.088	0.067	0.055	0.060
Initial Weight of Coal Sample (g)	2.500	2.500	2.500	2.500
Moisture (%)	3.520	2.680	2.200	2.400
Loss in Weight (g)	0.557	0.593	0.646	0.732
Weight of Coal Sample after Moisture (g)	2.412	2.433	2.445	2.440
Volatile Matter (%)	23.100	24.370	26.420	30.000
Weight of Ash (g)	0.176	0.237	0.162	0.250
Initial Weight of Coal Sample (g)	2.500	2.500	2.500	2.500
Ash (%)	7.040	9.480	6.480	10.000
Fixed Carbon (%)	66.340	63.470	64.900	57.600

Fuel Ratio	2.870	2.600	2.440	1.920

From Table 4.2, the coal from SM 3/1 has higher moisture content than the coal from the other three sections. The coal from SM 4/5 has a higher value of volatile matter than those from the other sections. According to Sarma and Morley (2018), coal with high moisture content is easier to grind while coal with high volatile matter is hard to grind.

This explains the friability of the coal from SM 3/1 and is consistent with the lithotype examination results, which show that the coal from SM 3/1 easily breaks. On the other hand, coal from SM 4/5 generates fewer fines since it has a higher volatility matter. This is also consistent with the lithotype examination results, which show that SM 4/5 breaks to form big lumps and fewer fines.

Mineral composition: Table 4.3 summarises the results of petrographic tests on minerals in MCM coal.

Table 4.3 Petrographic Test Results on Mineral Composition of MCM Coal

Section	Clays (% Vol.)	Quartz (% Vol.)	Opaque (Pyrite) (% Vol.)	Carbonates (% Vol.)	Other Minerals (% Vol.)	Not Visible (% Vol.)	Total (% Vol)
SM 3/1	86.6	3.6	1.4	5.2	0.6	2.6	100
SM 4/8	84.6	4.2	3.4	0.6	0.2	7.0	100
EM 1/1	74.4	6.6	1.6	4.2	0.4	12.8	100
SM 4/5	62.2	7.4	4.8	0.4	0.8	24.4	100

(Source: Anon., 2019)

Mineral composition: Minerals that dominate the mineral matter and associated with coal are clay, calcite, quartz, and pyrite (Table 4.3). According to Falcon and Falcon (1987), the hardness of clays and carbonates being low, 1 and 3 respectively, are considered to be soft. They contribute more to the friability of coal. On the other hand, minerals like quartz and pyrite which have hardness 7 and 6 respectively are considered hard and are not very friable (Raask, 1985; Wells *et al.*, 2005). The coal in SM 3/1 has high amounts of clay (86.6%) and carbonates (5.2%) and generate more fines during handling on conveyor belts and at transfer points.

The results are also consistent with lithotype examinations which show that SM 3/1 coal has more vitrain bands which can contribute to excess fines generation. The quartz and pyrite contents in coal from SM 4/5 are higher compared to the coal from the other three sections (see Table 4.3). The presence of high amounts of quartz (7.4% Vol.) and pyrite (4.8% Vol.) in SM4/5 section compare well with generation of lower amounts of fines.

Figure 4.8 shows that coal from SM 3/1 has a high value of friability of 31.25%. This is due to the high content of clays and carbonates while SM 4/5 has the least coal friability due to lower content of clays and carbonates, but high contents of pyrite and quartz as shown in Figure 4.9. The details from petrographic analysis of the minerals in MCM coal are summarised in Appendix 7.

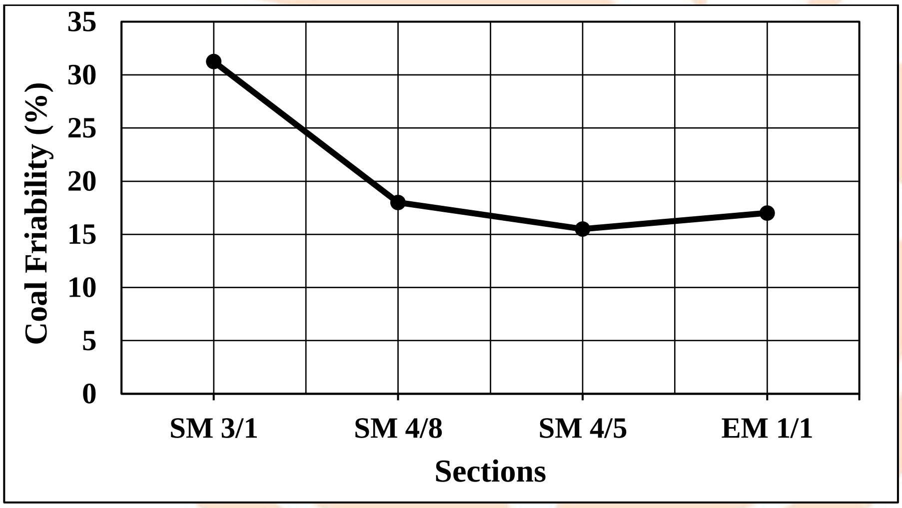

Figure 4.8 Coal Friability from MCM Sections

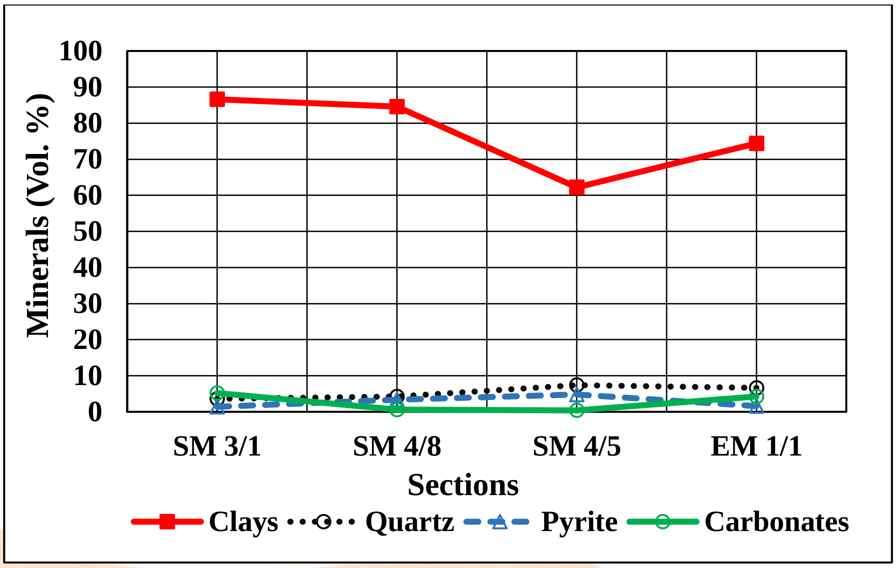

Figure 4.9 Mineral Content from MCM Sections

Vickers hardness test: Table 4.4 summarises the results calculated for Vickers's hardness using equation (6). From Table 4.4, the coal from SM 4/5 is much harder than those from the other sections. This may be due to the higher contents of quartz and pyrite as shown in Figure 4.10. SM 3/1 is the second least hard coal with a value of 30.65 kgf/mm^2 and has a higher content of clays and carbonates, which are known to be soft. The results of the drop shatter tests show that SM 3/1 is the most friable coal while SM 4/5 is the least friable due to the presence of hard minerals (quartz and pyrite). Since the hardness of coal is affected by different constituents, it is essential to focus on hardness more than the other results obtained from chemical and physical constituents.

Table 4.4 Results of Vickers Hardness (HV) of Coal

Sections	d_1 (mm)	d_2 (mm)	Mean (d, mm)	HV (kgf/mm^2)
SM 3/1	0.57	0.53	0.55	30.65
SM 4/8	0.58	0.54	0.56	29.56
EM 1/1	0.58	0.50	0.54	31.79
SM 4/5	0.55	0.51	0.53	33.0

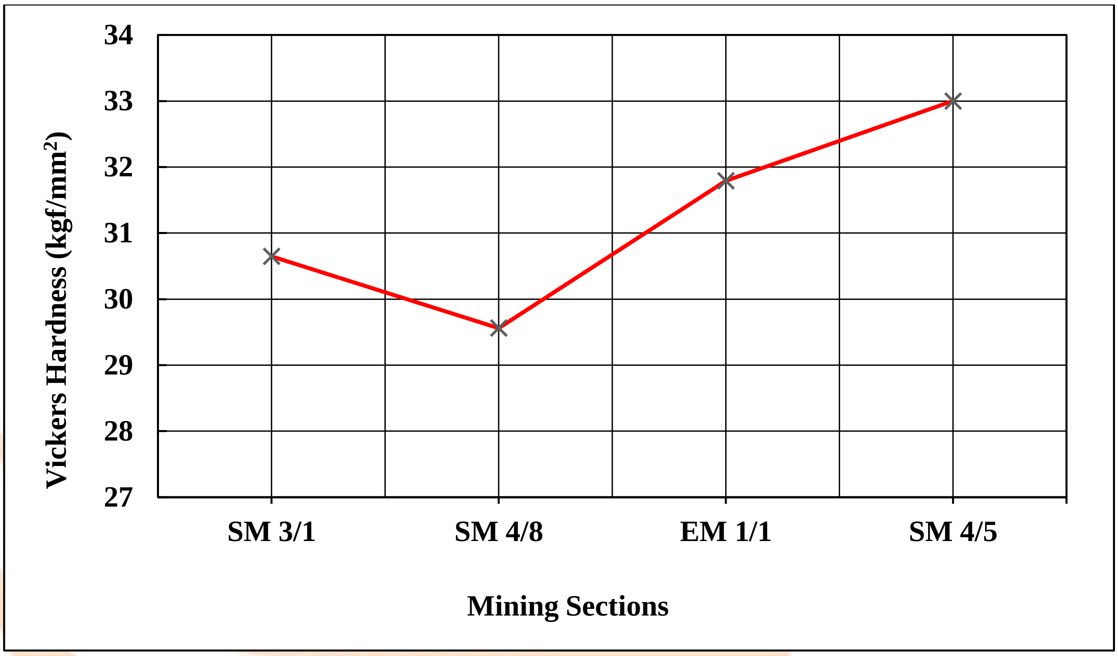

Figure 4.10 Vickers Hardness Results from MCM Sections

Also, from Table 4.5, SM 4/5 has the hardest coal compared to coal from the other sections and has the second least value of moisture content. Coal from SM 3/1 has the second least value of hardness but the highest moisture content. Figure 4.11 shows that the moisture content in coal is inversely proportional to the hardness of the coal. These results agree with the findings of Sarma and Morley (2018), who reported that coal with high moisture content is easier to grind compared to those with low moisture content.

Table 4.5 Vickers Hardness and Moisture

Sections	**HV (kgf/mm^2)**	**Moisture Content (%)**
SM 3/1	30.65	3.52
SM 4/8	29.56	2.68
EM 1/1	31.79	2.20
SM 4/5	33.00	2.40

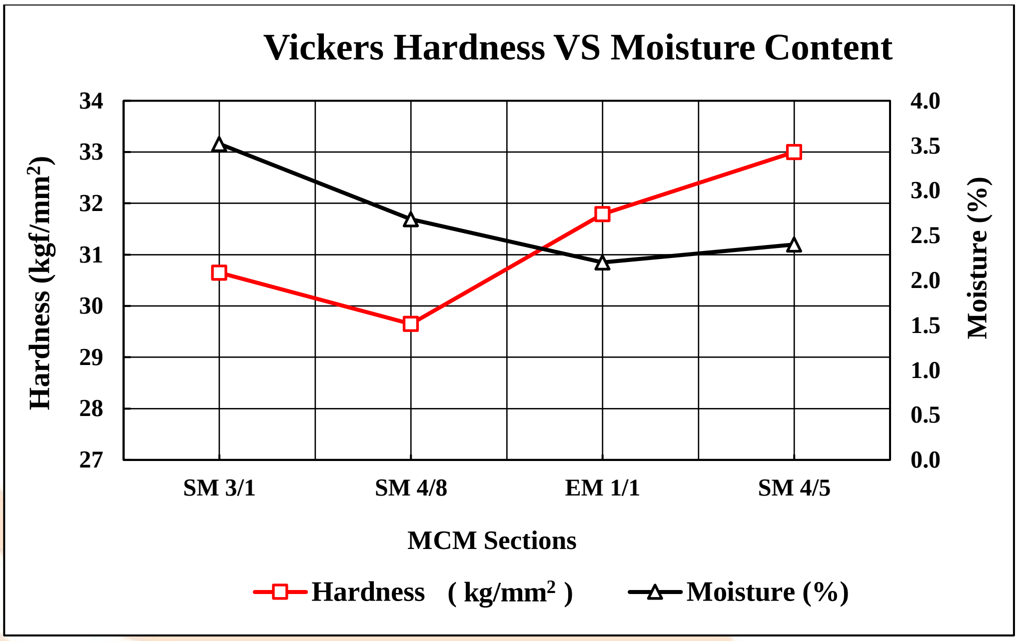

Figure 4.11 Effect of Moisture Content on Coal Hardness

SEM-EDS: Table 4.6 shows a summary of the concentration of the elements present in MCM coal. SM 3/1 coal has the lowest value of silicon (37.87%) while SM 4/5 coal has the highest value of silicon (41.00%). These results are consistent with the mineral composition data which showed that SM 3/1 coal has the lowest amount of quartz (3.6 % Vol.) while SM 4/5 coal has the highest amount of quartz (7.4 % Vol.) compared to other sections. Coal from SM 3/1 section also shows lower values for iron (6.21%) and sulphur (3.40%) combined, while SM 4/5 coal shows the highest values for iron (7.90%) and sulphur (4.90%) combined. These results are comparable with the mineral composition data which showed that SM 3/1 has the lowest amounts of pyrite (1.4% Vol.) while SM 4/5 coal has the highest content of pyrite (4.8% Vol.) compared to all three sections.

The most dominant element aluminium is comparable with clays where SM 3/1 coal having highest value for clays has the highest value of aluminium (28.31%) while SM 4/5 having lowest clays shows the lowest value for aluminium (26.67%). This is true for all sections. Calcium is comparable with carbonate minerals where coal from SM 3/1 shows relatively higher amounts if carbonates and also Ca values.

Table 4.6 Results of SEM-EDS Analysis of Coal from Four Sections, Morupule Mine

Elements	**SM 3/1**	**SM 4/8**	**EM 1/1**	**SM 4/5**
Ca (%)	9.00	8.40	8.60	8.50
K (%)	0.38	0.40	0.41	0.39
Mg (%)	2.50	3.01	2.48	2.52
Al (%)	28.31	27.01	27.88	26.67
Na (%)	1.28	1.26	1.24	1.21
Mn (%)	2.09	2.04	2.06	1.72
Ti (%)	4.80	4.05	4.46	3.04
P (%)	3.16	3.02	3.18	2.15
Fe (%)	6.21	6.61	5.39	7.90
Si (%)	37.87	38.46	39.41	41.00
S (%)	3.40	5.74	4.89	4.90

(Source: Anon., 2019)

Cutting by continuous miner: The cutting efficiency of the continuous miner is dependent on the drum, cutting picks (angle of attack and line spacing) and operator's skill. Therefore, the cutting action and cycle of the continuous miner were observed on several occasions to determine the effects on fines generation.

Cutting cycle: The CM follows the proper cycle of cutting which includes sumping, shearing and grading back.

Conditions of drum including regular bit replacement: The drum of the CM was in proper condition as the CM went through periodic maintenance. The picks were replaced regularly at the beginning of every shift of 8 hours. It was observed that at the end of an 8-hour shift, usually, the picks became blunt, which leads to grinding the coal during cutting. Hence, they generate more fines.

Skill of operator: The performance of the operators was observed in the four sections on separate occasions. The results show that most of the CM operators have good skills. For example, when the seam widths changed, the operators were able to notice it from the noise from the drum CM when it was cutting the coal. They were able to adjust the speed of the drum to match the type of seam encountered. Table 4.7 summarises the cutting parameters of the continuous miners at MCM.

Table 4.7 CM Cutting Parameters

Cutting Parameters	Specification	MCM 12HM 31 CM
Angle of Attack	45° - 55°	51°
Back Clearance Angle	5° - 10°	9°
Line Spacing (mm)	40 - 60	56

The optimal line spacing ranges from 40 mm to 60 mm if line spacing is too close the cutting is inefficient due to over-crushing leading to fines generation. The optimal cutting angle is between 45^o to 55^o, cutting at an angle of 55^o reduces the amount of fines generated more significantly than when cutting at 45^o. From the literature, the back-clearance angle should be greater than 5° but less than 10° (Raghavan, 2014). From the values in Table 4.7, the cutting parameters of the continuous miners MCM 12HM 31 fall within the optimal range for all cutting parameters. Thus, MCM selected the right types of continuous miners for the types of coal that occurs at MCM.

4.3 ROM Stockpile Coals

Figure 4.12 shows the PSD of coal after obtaining a composite sample of 20 kg from four different places of the ROM stockpile, which represents the overall PSD of coal from the system. D27 is the size of the sieve from which 27% of the coal is passing. It shows that the average quantity of fines generated by the system is < 3.35 mm.

Fines generation occurs at every stage throughout the whole haulage system from feeder breakers at the mining section which is less than 10% which is within acceptable limits. Fines generation at the lowest transfer point is 4% and at the highest transfer point is 9%. Fines generation by the slowest conveyor is 4% and fastest is 15%. Finally, at the run-off-mine stockpile which gives a reasonable approximation of fines generation as a whole is 27%.

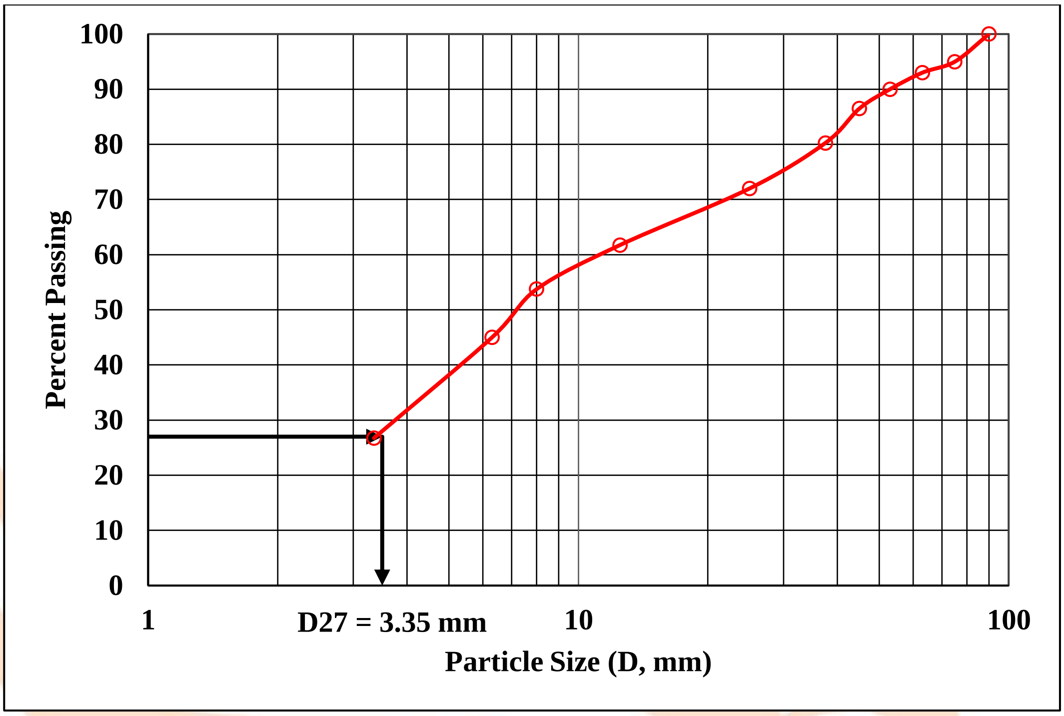

Figure 4.12 PSD of Runoff Mine Stockpile Coal

4.3.1 Sensitivity Analysis

The relative influence of feeder breakers (FB), belt speeds (BS) and transfer points (TP) on fines generation at the run-off-mine (ROM) stockpile based on particle size distribution is evaluated by the cosine amplitude method (CAM). Table 4.8 summarises the CAM results.

Table 4.8 CAM Results

Baseline (ROM) (% Passing)	FB (% Passing)	BS (% Passing)	TP (% Passing)
100.00	100.00	100.00	100.00
95.00	69.26	83.33	82.00
93.00	46.50	71.33	72.00
90.00	36.50	55.33	58.25
86.50	27.58	44.66	43.75
80.25	24.28	33.33	34.25
72.00	21.83	29.00	29.62
61.75	18.56	26.00	25.00
53.75	15.00	20.33	20.25
45.00	10.51	14.00	14.70
26.75	6.155	9.66	10.87
Strength Values	0.70	0.95	0.97

According to strength values obtained from the application of the CAM (Figure 4.13) feeder breakers have the least influence, followed by speed of conveyors, and finally transfer points (height) is the most influencing parameter on fines generation at the run-off-mine stockpile (ROM).

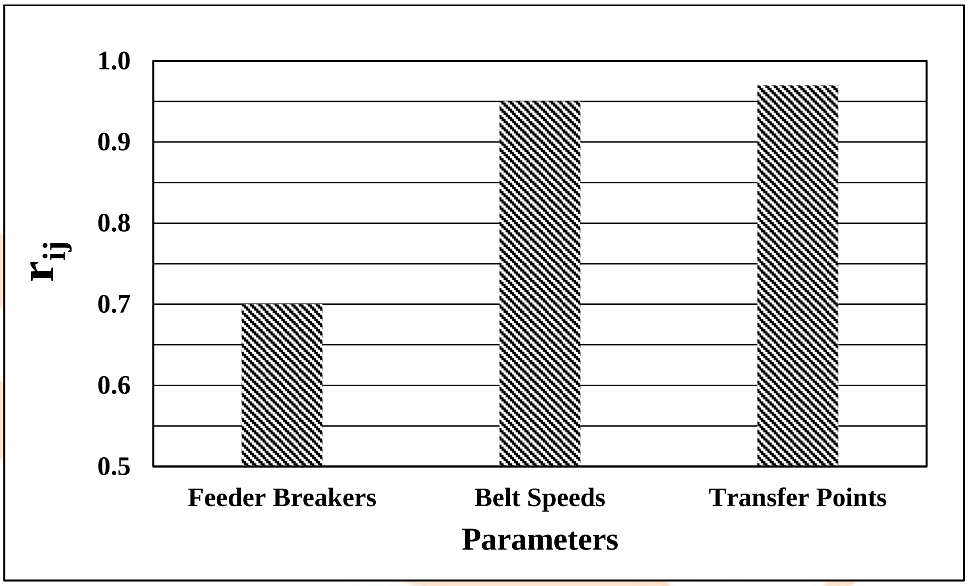

Figure 4.13 Sensitivity Analysis Using CAM

4.4 Impact of Fines on Production and Economic Losses

Analysis was carried out to determine the production losses as a result of tail end blocking or conveyor belt breakdowns; losses at the Wash Plant as a result of not meeting the targets; and increasing engineering control costs as a result of the generation of more fines.

4.4.1 Coal Wash Plant Losses

MCM Coal Wash Plant Capacity: 400,000 tonnes per annum

Feed Rate: 200 tph

Actual: 370,060 tonnes in a year

Total Fines: 11.11% in a year

Average of Fines = $\left(\frac{11.11}{12}\right) \times 100\% = 0.9\%$ monthly

Acceptable Limit (Fines) = 0.5%

The CWP Product and Fines (%) are summarised in Appendix 8.

Figure 4.14 shows that the fines generation is one of the significant factors due to which the targets are not met at the Wash Plant for most of the months. This suggests that significant amount of coal gets washed away as waste in the form of fines at Wash Plant. Most customers accept coal products with a limited percentage of fines. When the composition of fines in the stockpiles constitute more than 20% of the overall stockpile, then the targets (fines should make only 0.5% of the coal feed into the plant) would not be met at the Wash Plant. For example, BPC requires coal products with less than 32% fines. On average, fines contribute 0.9% of coal fed into the Wash Plant which is beyond the acceptable limit of 0.5%.

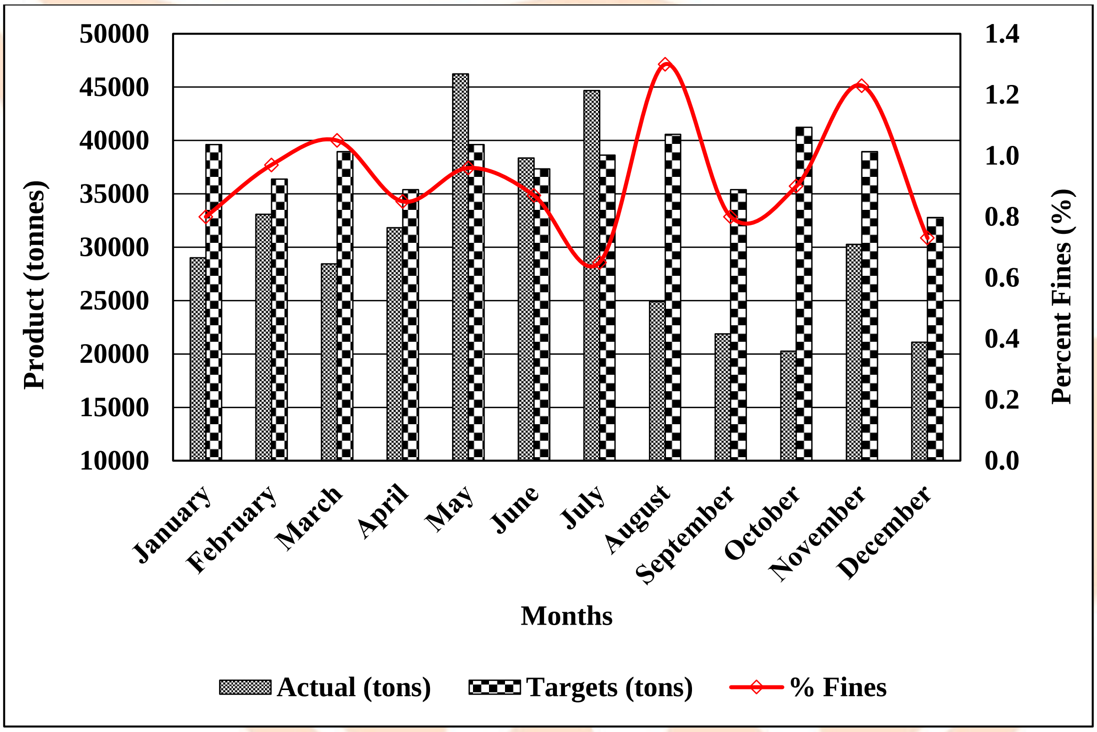

Figure 4.14 Coal Wash Plant Product

4.4.2 Conveyor Belt Performance

Average MCM Production = 4,100 tonnes/shift.

Conveyor Belt Blockage Delay (Monthly) = 77.57 hours

Average Number of shifts (Monthly) = 23 shifts (3 shifts/day)

Delay per shift =77.57 hrs/23 shifts = 3.37 hr

Production Loss = $\left(\frac{4{,}100 \text{ tonnes} \times 3.37 \text{ hr}}{8 \text{ hr} \times 3 \text{ shifts}}\right)$ = 575 tonnes/shift = 1,727.13 tonnes/day

The conveyor belt performance parameters are summarised in Appendices 9 and 10.

Figure 4.15 shows that conveyor belt blockage is the major cause of delays conveyor belt than other conveyor belt problems. These blockages result from fines generated. The cumulative delay from the conveyors is 77.57 hours every month (i.e., an average of 3.37 hr/shift). The average coal production at MCM in an 8-hour shift is 4,100 t. Therefore, the delays due to conveyor belt blockage led to production loss of 575 tonnes per shift. The anomalies in the month of August and November where more fines were generated while less coal was produced is due to a relatively weak seam that was encountered during mining in those months from the SM 3/1 mining section.

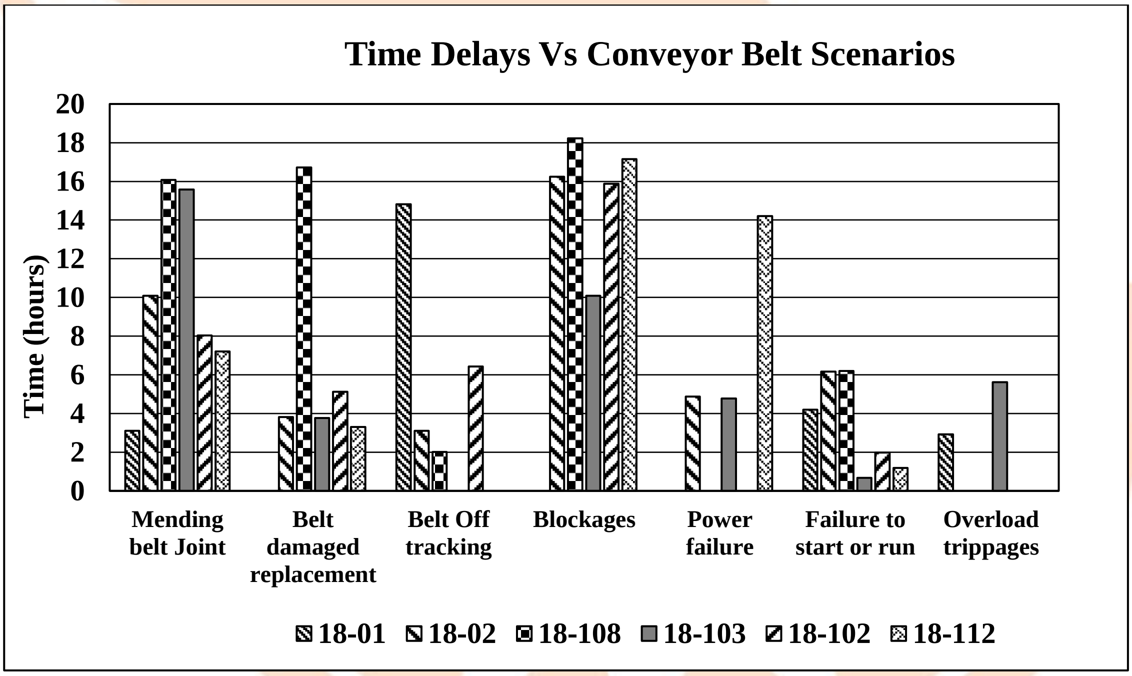

Figure 4.15 MCM Conveyor Belt Performance

Figure 4.16 shows the blockages recorded at individual conveyor belts. It can be observed that the main conveyor belts (i.e., 18-108, 18-111, 18-112) had lower downtimes than section conveyor belts. The main conveyor belt 18-103 has the highest downtime of 18.22 hr per month. This is because belt 18-103 is connected to the tail-end (pulleys that drive the belt and where it rotates). Hence, fine coal tends to clog or accumulate at the end of the pulleys resulting in severe blockages.

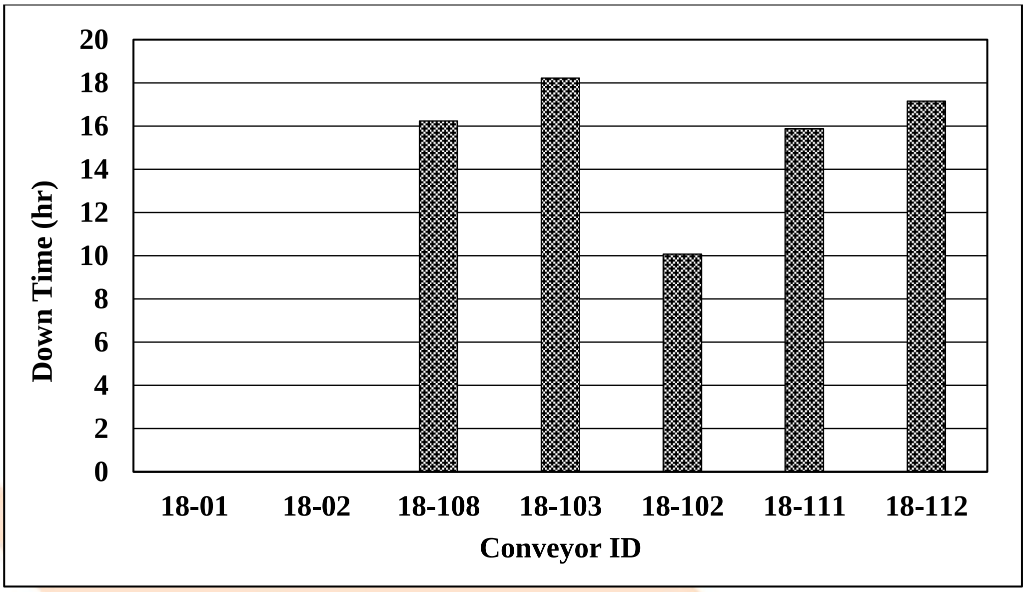

Figure 4.16 Blockages for Individual Conveyors

Figure 4.17 shows the production losses versus breakdown times. It shows that production losses are directly proportional to breakdown times. This was the general trend in all the months. The leading cause of conveyor breakdowns was tail end blockages due to fines accumulation.

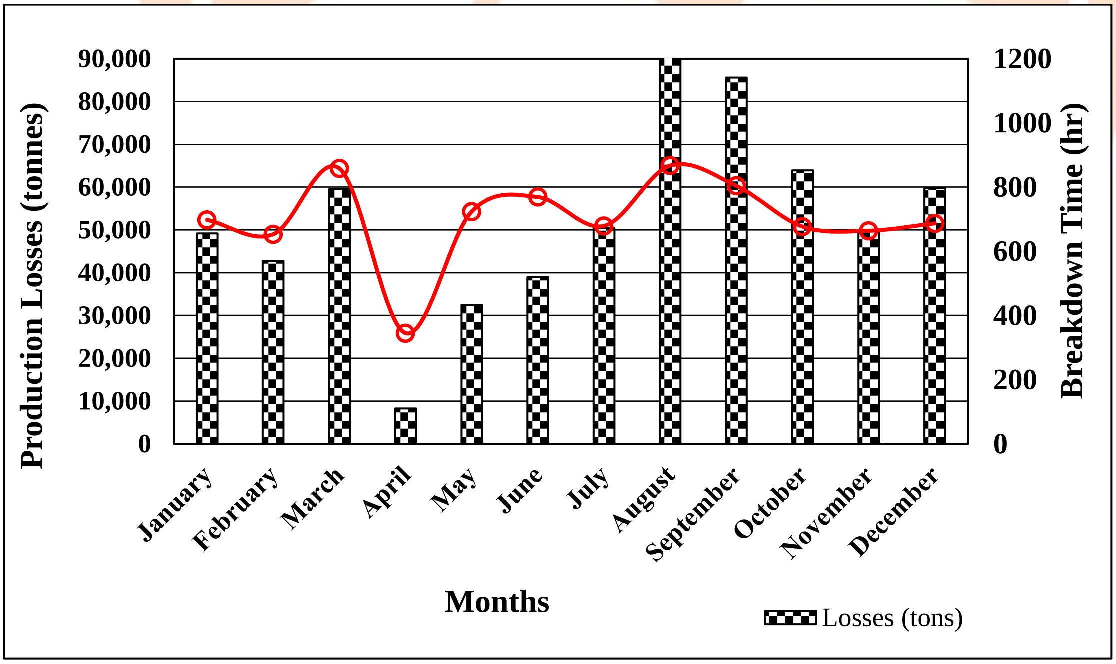

Figure 4.17 Relation between Production Losses and Conveyor Breakdowns

4.4.3 Engineering Controls

Figure 4.18 shows the engineering control of the main ventilation system at MCM. From Figure 4.18, the quantity of intake air supplied does not vary based on the quantity of fines generated. The main fans are operated continuously at their designed capacities of 600 m^3/s. Hence, fines generation does not lead to significant costs for ventilation supplied.

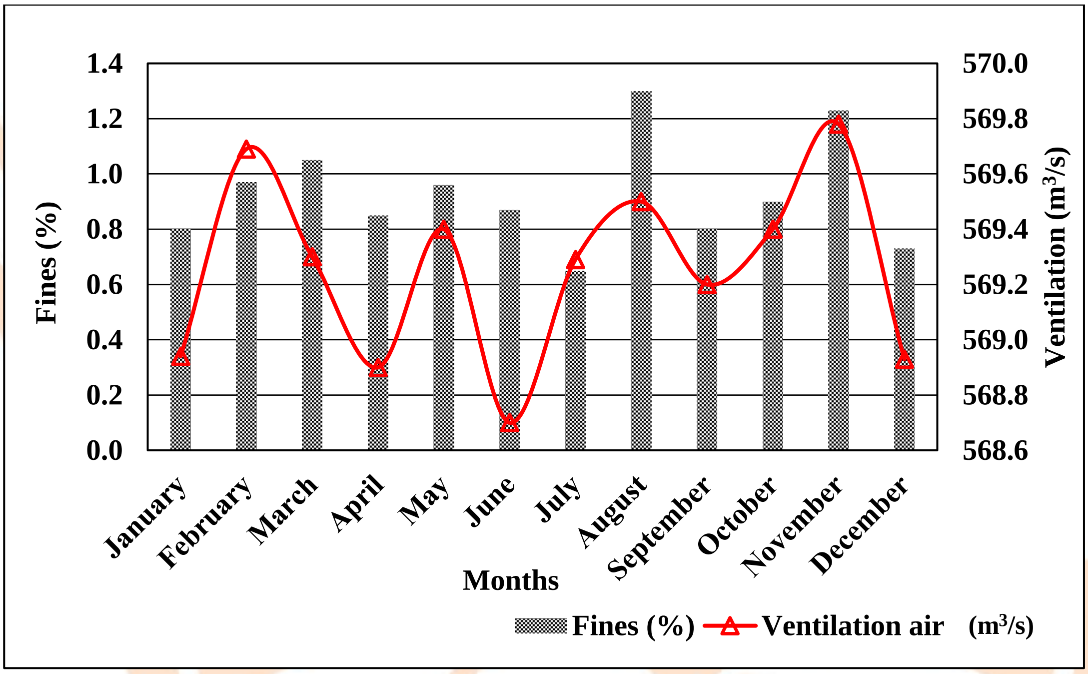

Figure 4.18 Engineering Control Main Ventilation

4.4.4 Economic losses

Coal Price = BWP650/tonne

Actual Output (wash coal) = 370,060 tonnes/year

Fines (wash plant) = 11.11% in a year.

Acceptable Limit = 0.5%/monthly × 12 = 6% in a year

Loss (Fines) = 11.11% - 6% = 5.11%

Production Loss = 191 tonnes/shift

Economic Loss from Production = P650/tonne × 575 tonnes/shift = BWP 373,750.00/shift

$$\text{Economic Loss from Wash Plant} = \left(\frac{\frac{\text{P650}}{\text{tonne}} \times 5.11\% \times 370{,}060\ \text{tonnes/year}}{\frac{12\ \text{months}}{\text{yr}} \times 23\ \text{shifts/month}} \right)$$

$$= \text{BWP}44{,}534.57/\text{shift}$$

The total monetary loss per shift is BWP 373,750 + 44,534.57 = BWP 418,285

The loss per shift is significant and could be saved if proper measures are put in place to address the fines generation. The losses are incurred at both the Wash Plant and along conveyor belts due to blockages which cause delays in production as a result of fines.

4.5 Environmental Evaluation

An assessment of the environmental impact of dust generation is carried out with the use of a Leopold matrix as shown in Table 4.9 as an impact identification tool. This also includes evaluating the impact of dust generation on the health and safety of workers and equipment.

4.5.1 Human Health

In the Leopold matrix, the magnitude for cutting of the continuous miner is low since this activity only affects the area where the CM is cutting at the section. Loading and dumping of shuttle cars have low magnitude as well since they involve only specific areas where loading and dumping operations are done. The magnitude is also low for haulage by conveyor belts because it only affects the locations around transfer points where fines are generated.

Table 4.9 Leopold Matrix for Impact Identification

Valued Components	**Coal Handling Operations**			
	Cutting of CM	**Hauling of shuttle cars**	**Transporting coals**	**Stockpiling coal**
Human Health	3 / 9	3 / 6	2 / 6	6 / 9
Machinery	2 / 8	3 / 8	2 / 2	2 / 2
Air quality	1 / 2	1 / 1	3 / 1	1 / 2
Total	45	43	19	60

Stockpiling of coal has the highest magnitude since it is done on the surface, and the coal dust gets dispersed into the atmosphere over a large area around the mine. The importance of all the activities is directly linked to human health as coal dust has detrimental effects on human health, leading to severe diseases such as black lung and lung cancer.

The mine employs the following strict measures to prevent coal dust dispersion and inhalation by mine workers. As a result, there has not been any reported cases of coal workers pneumoconiosis.

Training programmes: The mine has training programmes in place for all coal miners and other workers exposed to respirable coal mine dust. Training is given when a new job is assigned, and workers are informed about the health and safety hazards of the site. Training includes information about procedures workers must take to keep themselves from exposure to respirable dust.

Posting: All warning signs and directives are printed and posted to inform workers about dangerous areas.

Engineering controls: Engineering controls in the mine are the principal methods used to reduce exposure to respirable coal mine dust. Engineering control measures include diluting the dust generated (by adequate ventilation at the coal face), controlling the respirable dust created and entrained (with improved shearer drum design of the CM), and suppressing the dust generated utilizing water.

Protective clothing and equipment: Workers wear approved work uniforms and coveralls that are laundered each day. The protective clothing is inspected and maintained to preserve its effectiveness.

Respiratory protection: Engineering controls are used to control undue exposure to airborne contaminants. Workers use respirators during the development, installation, or testing of required engineering controls and when engineering controls are not viable to control exposure to airborne pollutants.

Exposure monitoring: Environmental monitoring is done to protect workers from the adverse effects of exposure to respirable crystalline silica and coal mine dust. Monitoring allows for the evaluation of the effectiveness of engineering controls and work practices.

Competent industrial hygienists and engineering personnel carry out environmental monitoring (initial and periodic surveys).

The concentration of respirable coal dust is determined as a Time Weighted Average (TWA) by collecting samples over an 8-hour shift for up to a 40-hr work week. When it is observed that the respirable dust concentrations exceed the Recommended Exposure Limit (REL) for respirable coal dust or respirable crystalline silica, workers wear respirators for protection until adequate engineering controls or work practices employed return the atmosphere to normal levels.

MCM ventilation standards which complies to the Mines, Quarries, Works, and Machinery Act Chapter 44 of Botswana limits the dust concentration underground to 2 mg/m^3. As shown in Figure 4.19, the dust level concentrations are kept within the acceptable limits in the mine as the dust concentrations underground were all < 2 mg/m^3.

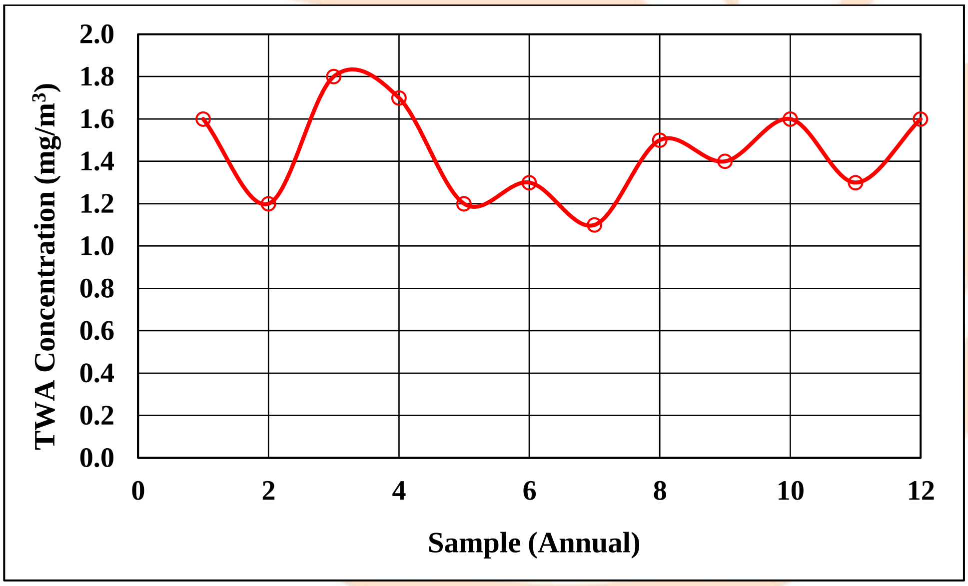

Figure 4.19 Underground Coal Dust Concentration in MCM

Medical screening and surveillance: Priority in the mine is given to primary inhibition of occupational respiratory diseases through the decrease of exposures. A secondary programme of medical detection and monitoring is also carried out to identify miners who develop respiratory diseases because of their workplace exposures.

4.5.2 Machinery

The magnitude for cutting of the CM, loading, and dumping by shuttle cars in the Leopold matrix is low because it only affects the machines. Still, the value or importance is high since these machines are critical to coal mining and handling and any breakdown or delay from the CMs cause serious production losses.

Machinery such as continuous miners and roof bolters are not significantly affected by the coal dust since they are designed with dust collection systems to deal with the dust. In cases where dust collectors of the roof bolters show accumulations of dust between the filters and blower, the dust is removed by backflushing the system with compressed air. The continuous miner is remote controlled in most cases to enable the operators to avoid dusty areas and remain in fresh air to minimise their dust exposure.

The CMs are also equipped with sound non-clogging water filtration systems to avoid cases where dirt and dust particles in the water line clog the spray nozzles. Regular bit replacement and routine inspections of the cutting drum are done to minimise fines generation.

4.5.3 Air Quality

The magnitude for conveying by belts (on the surface) and stockpiling of coal in the Leopold matrix is high since these activities are exposed to the atmosphere and affect a more significant area around the mine. Its value is very high since the coal dust in the atmosphere has effects on human health and vegetation on the mine and surroundings.

Coal screening, stockpiling, and loading are the primary sources of particulate matter (coal dust) at the colliery. MCM monitors the air quality of its underground operations as well as above ground for occupational reasons. The results of the coal dust monitoring taken above the surface are shown in Figure 4.20, the air quality around the mine is 0.30 g/m^3. Table 4.10 shows the World Bank Group's coal dust limits within average periods. The results show that the World Bank threshold limits (0.05 g/m^3) for ambient air quality based on annual average periods were exceeded. Figure 4.20 also shows that the Botswana Waste Management Act (BWMA) limits for particulate matter of 0.1 g/m^3 based on annual averaging period were also exceeded. As a result of this, fine coal dust particles settling on the soil and affect the quality and pH of the soil. Dust deposition on the leaves of plants decreases photosynthesis in the plants (e.g. chloroplast content and stomatal blockage) and affects the colour of the leaves and plant growth. It was observed that the leaves of the vegetation around the area had dull green colour and most plants had stunted growth.

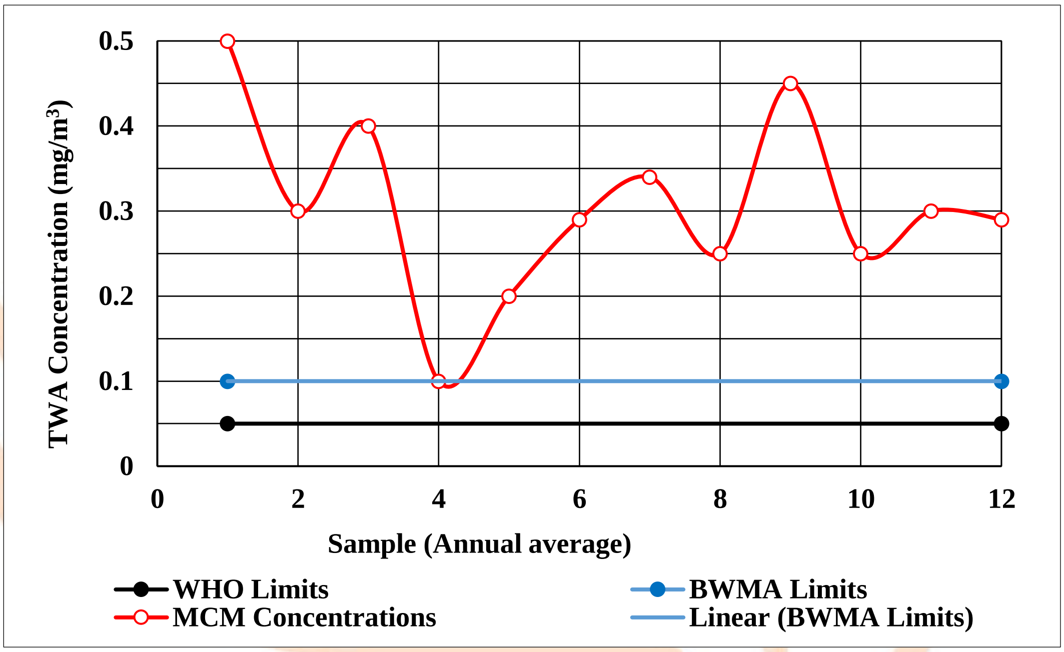

Figure 4.20 Surface Coal Dust Concentration in MCM

Table 4.10 World Bank Group Gases and Coal Dust Limits

Averaging Period	**World Bank Limit (mg/m³)**		
	SO_2	**NO_2**	**PM_{10}**
1 hr	No limit	No limit	No limit
24 hr	0.15	0.15	0.15
Annual average	0.15	0.1	0.05

(Source: Anon., 2007)

4.5.4 Summary of Impacts

Human health is affected by all activities in coal handling operations. However, activities such as conveying coal by belts and stockpiling have the most significant impacts on air quality around the mine. Coal handling operations of high magnitude (extent of impact) have led to more significant impacts (magnitude of x-value).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From the analysis in this work, it is concluded that:

- The major causes of fines generation are transfer points, especially the surge bin, which contributes about 9%. This is because of the impact that takes place as coal drops from a height and the abrasion that takes place during conveying.
- The speed of the conveyor belt also contributes about 8% fines generated due to abrasion between coal particles being conveyed.
- The results from the drop shatter test show that SM 3/1 coal is the most friable with value 31.25% and SM 4/5 coal is the least friable with a value of 15.5%. These results are consistent with coal petrography which shows that coal from SM 3/1 has a higher content of soft clay minerals (86.6% Vol.) and carbonates (5.2% Vol.). However, coal from SM 4/5 section is the hardest due to presence of relatively higher amounts of hard minerals, quartz and pyrite.
- The results of petrographic tests on the coal show that SM 3/1 coal has the lowest quantity of silicon (37.87%) while SM 4/5 coal has the highest content of silicon (41.00%). Silicon forms quartz which is a hard mineral. The most dominant element is aluminium which is found in clays where SM 3/1 coal has the highest content of aluminium (28.31%) while SM 4/5 has lowest content of clays with 26.67% aluminium.
- The overall haulage system from the working face to the run-off-mine stockpile was found to generate about 27% of fines of the coal produced monthly.
- Blockage of the tail ends of conveyors by fines results in about 575 tonnes per shift production losses.
- Fines constitute about 0.9% of coal fed into the Wash Plant which exceeds the required 0.5% limit and leads to significant losses at the plant.
- The total monetary loss per shift is about BWP 418,285 from both the Wash Plant and production zones.
- From the Leopold matrix, stockpiling of coal has a greater magnitude and the highest impact significance of 117 because this is where the coal dust gets spread into the

atmosphere extensively. Thus, the ambient air quality of the mine is 1.18 g/m^3 which exceeds the World Bank Limits of 0.15 g/m^3 based on 24 hr averaging period. As a result of this the vegetation around the mine area is adversely affected as the colour of the leaves is altered.

- The mine employs strict engineering control measures to prevent coal dust dispersion and inhalation by mine workers. As a result, there has not been any reported cases of coal workers pneumoconiosis.

5.2 Recommendations

It is recommended that:

1. The height of transfer points (e.g. at the surge bin) should be reduced since the speed of the conveyors cannot be reduced as this will compromise coal production.
2. Deflection plates could be used on chutes to reduce the impact as well as cushioning of surge bin with rubber to minimise the impact as well as reducing the noise pollution from the impacts.
3. Fines produced during operations should be collected and used for coal pyrolysis and agglomerated for sale.

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APPENDICES

APPENDIX 1

PROCEDURE FOR SAMPLING ON CONVEYOR

Shovelfuls termed increments are taken from the belt. A sampler stands at a fixed point and takes increments at fixed time intervals by including a complete cross-section of the belt. When sampling from a stationary belt, most of the sample is removed with a shovel and the remainder with a brush. The increments are then combined into one sample.

APPENDIX 2

PROCEDURE FOR SAMPLING ON A STOCKPILE

The first stage of sampling that is primary sampling is the taking from positions distributed over the entire range of an adequate number of coal portions, and this is primary increments. To reduce the mass of the sample to a manageable size, the primary increments are then combined into a sample. The required number and types of test samples were then prepared. Before extracting the increments, the surface is adequately compacted to bear the weight of personnel and equipment. A manual probe was used, the aperture of the probe had a dimension of 30 mm. The surface of the stockpile was divided into several squares using an imaginary grid system.

By removing the coal top surface, the manual probe is then inserted at right angles to the coal surface. Large pieces of coal were deliberately pushed aside when an increment is extracted. A full column of coal was extracted so that a representative increment is taken. Water spraying was carried out when sampling from a freshly exposed surface of a stockpile. One composite sample of 20 kg was obtained at four different places of the stockpile.

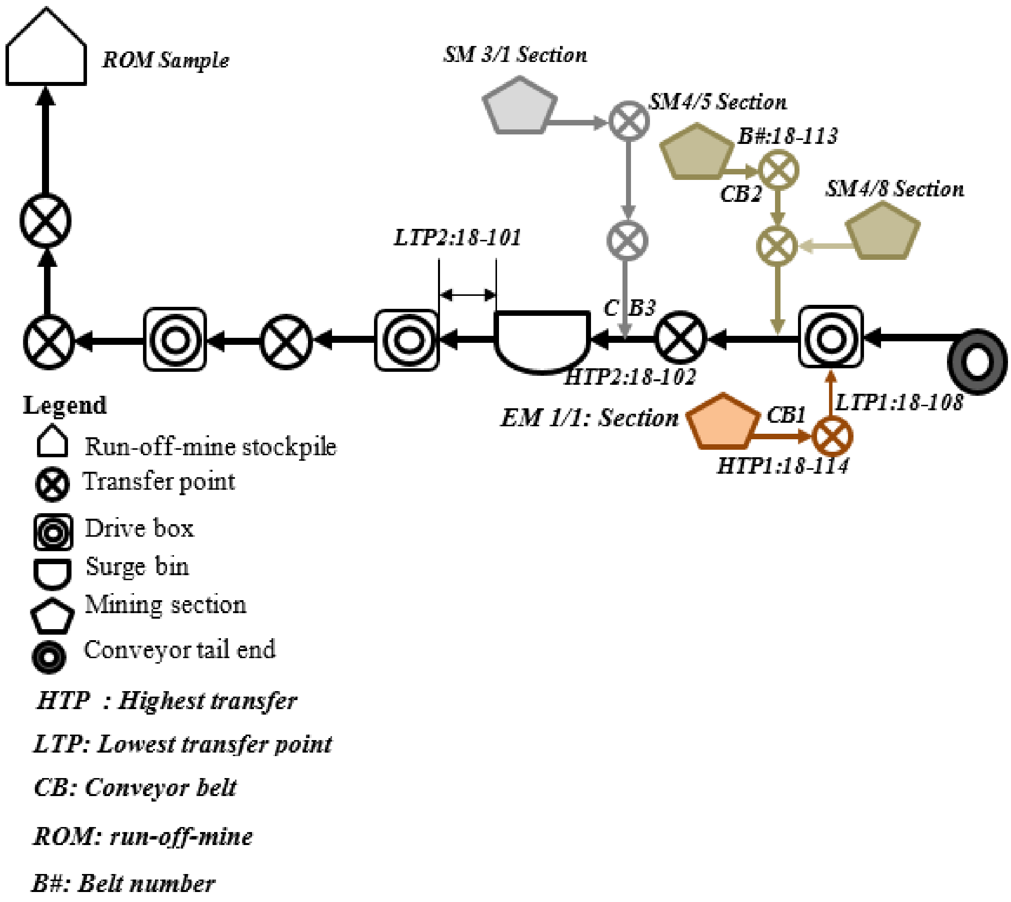
APPENDIX 3

SAMPLE DESCRIPTION

Sample	Description
SM 3/1	20 kg sample from South Main 3/1 section
SM 4/8	20 kg sample from South Main 4/8 section
SM 4/5	20 kg sample from South Main 4/5 section
EM 1/1	20 kg sample from East Main 1/1 section
CB1	20 kg sample from slowest speed conveyor belt number 18-114, near HTP1 sample.
CB2	20 kg sample from medium speed conveyor belt number 18-113.
CB3	20 kg sample from fastest conveyor belt number 18-102, near the HTP2 sample.
HTP1	20 kg sample before transfer point, belt number 18-114.
HTP2	20 kg sample from before transfer, point belt number 18-102.
LTP1	20 kg sample after transfer point, belt number 18-108.
LTP2	20 kg sample after transfer point, belt number 18-101.
ROM	20 kg sample from run-off-mine stockpile.

APPENDIX 4

SAMPLE LOCATION



APPENDIX 5

PROCEDURE FOR PROXIMATE ANALYSIS

For determination of moisture content, 2.5 g of finely powdered coal is weighed in a silica crucible, and the crucible is placed without lid in an electric hot air oven, kept at 105 ^{o}C to 110 ^{o}C for an hour. The Crucible is then taken out, cooled in a desiccator, and weighed for loss in weight.

For determination of a volatile matter, the same crucible is covered with a lid and placed in a muffle furnace maintained at 925 ^{o}C for 7 minutes. The crucible is cooled in air and then in a desiccator and weighed again.

For determination of ash, the residual coal in the crucible is heated without lid (ash is incombustible matter to lose other components and remain with ash) in a muffle furnace at 700 ^{o}C for an hour. The crucible is then taken out, cooled first in the air then in a desiccator, and weighed. The residue is reported as ash on a percentage basis. For the determination of carbon, the percentage of moisture, volatile matter, and ash is subtracted from 100%.

APPENDIX 6

MCM CONVEYOR BELT SPECIFICATION

Specification 1

Belt Specification	**01**	**02**	**101**	**102**	**103**
Width (mm)	1350	1350	1500	1500	1500
Capacity (tph)	2880	2880	2880	2880	2880
Speed (m/s)	4.91	4.92	4.62	5.5	4.33
Power Packs (kW)	3 × 250	2 × 250	4 × 250	3 × 250	3 × 250
Belt Length (m)	435	132	1346	1435	1467
Belt Height (m)	45.5	28	32.1	34.5	13.1

Specification 2

Belt Specification	**18-100**	**18-110**	**18-111**	**18-112**	**18-113**
Width (mm)	1,350	1,050	1,050	1,350	1,350
Capacity (tph)	1920	960	960	960	960
Speed (m/s)	5.05	5.08	2.71	5.08	5.05
Power Packs (kW)	3 × 250	2 × 110	2 × 110	2 × 110	1 × 110
Belt Length (m)	1,303	830	1,061	50	880
Belt Height (m)	6.1	24	1.0	1.0	8.4

Specification 3

Belt Specification	**18-114**	**18-115**	**18-108**
Width (m)	1,050	1,350	1,050
Capacity (tph)	960	960	960
Speed (m/s)	2.28	5.13	5.06
Power Packs (kW)	2 × 110	3 × 110	4 × 110
Belt Length (m)	952	600	1,480
Belt Height (m)	11.5	1.4	1.6

APPENDIX 7

MCM MINERAL DATA

Mineral	Field of View (%)	Name of Section			
		SM 3/1	SM 4/8	EM1/1	SM4/5
Clays (% Vol.)	5 - 20	59.6	69.2	70.8	51.6
	20 - 60	22.8	10.2	2.8	8
	> 60	4.2	5.2	0.8	2.6
	Total	86.6	84.6	74.4	62.2
Carbonates (% Vol.)	5 - 20	1.8	0.4	0.6	0.4
	20 - 60	1.4	0.2	2.0	0
	> 60	2	0	1.6	0
	Total	5.2	0.6	4.2	0.4
Pyrite (% Vol.)	5 - 20	0.8	2.0	1.4	0.8
	20 - 60	0.6	0.6	0.2	2
	> 60	0	0.8	0	2
	Total	1.4	3.4	1.6	4.8
Quartz (% Vol.)	5 - 20	1.6	1.8	5.2	4.6
	20 - 60	1.8	1.4	0.8	1.4
	> 60	0.2	1	0.6	1.4
	Total	3.6	4.2	6.6	7.4
Other Minerals (% Vol.)	5 - 20	0.4	0	0.2	0
	20 - 60	0.2	0	0.2	0
	> 60	0	0.2	0	0.8
	Total	0.6	0.2	0.4	0.8
Not Visible (% Vol.)	< 5	2.6	7.0	12.8	24.4

APPENDIX 8

COAL WASH PLANT PRODUCT (2019)

Month	CWP Product (tonnes)	CWP Targets (tonnes)	Fines (%)
January	29,025	39,616	0.80
February	33,072	36,369	0.97
March	28,441	38,966	1.05
April	31,826	35,394	0.85
May	46,235	39,616	0.96
June	38,345	37,343	0.87
July	44,687	38,642	0.65
August	24,906	40,590	1.30
September	21,888	35,394	0.80
October	20,254	41,239	0.90
November	30,276	38,966	1.23
December	21,105	32,797	0.73

APPENDIX 9

MCM CONVEYOR BELT BREAKDOWN TIMES (AVERAGE MONTHLY)

Type of Conveyor Breakdown	01	02	108	103	102	111	112	Total (hr)
Mending joint/splicing (hr)	6.28	3.10	10.08	16.08	15.58	8.04	7.20	66.36
Replacement & extension (hr)	2.95	0.00	3.82	16.72	3.77	5.12	3.31	35.69
Belt off tracking (hr)	0.30	14.81	3.11	2.01	0.00	6.43	0.00	26.66
Blockage (hr)	0.00	0.00	16.24	18.22	10.08	15.88	17.15	77.57
Power failure (hr)	0.92	0.00	4.87	0.00	4.78	0.00	14.21	24.78
Failure to start or run (hr)	0.00	4.20	6.17	6.20	0.67	1.98	1.18	20.40
Overload trippages (hr)	0.00	2.93	0.00	0.00	5.62	0.00	0.00	8.55

APPENDIX 10

MCM MONTHLY PRODUCTION (2019)

Month	Actual (tonnes)	Target (tonnes)	Losses (tonnes)	Breakdown Times (hrs)
January	184,842	234,000	49,158	698
February	181,235	224,000	42,765	653
March	180,500	240,000	59,500	858
April	209,757	218,000	82,43	345
May	211,513	244,000	32,487	724
June	191,078	230,000	38,922	769
July	187654	238,000	50,346	679
August	146,752	250,000	103,248	867
September	138,431	224,000	85,569	804
October	156,117	240,000	83,883	677
November	180,048	230,000	49,952	664
December	160,306	220,000	59,694	687