Characterisation of airborne dust in South African underground and opencast coal mines: A pilot study

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Dissertation submitted in partial fulfillment of the requirements for the degree *Magister Scientiae* in Occupational Hygiene at the Potchefstroom Campus of the North-West University

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May 2015

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Preface

For the aim of this mini-dissertation it was decided to use article format. The article is written according to the guidelines of the journal Annals of Occupational Hygiene which is the chosen journal for potential publication. The journal requires that the references in the text should be in the form Jones (1995), or Jones and Brown (1995), or Jones *et al*. (1995) if there are more than two authors. References should be listed in alphabetical order by name of first author, using the Vancouver Style of abbreviation and punctuation.

Chapter 1 provides a brief introduction to the coal mining industry and the dust associated with this industry which, up until now, have not been clearly characterised. Furthermore, it includes the problem statement and hypothesis. Chapter 2 consists of a discussion of the coal mining process, the characteristics of dust, the dangers of coal dust including the health effects, the role of nanoparticles and the sampling methodologies used in this study. Chapter 3: The Characterisation of airborne dust in South African underground and opencast coal mines: A pilot study, is written in article format. All Tables and Figures are included here, along with text, to present the findings of this study in a readable and understandable format. For the purpose of examination the methodology and results are presented in detail and subsequently the maximum length of the article is exceeded. The article will be shortened before being submitted to the Annals of Occupational Hygiene for peer reviewing and publication after examination. Chapter 4 includes a final summary and conclusion, as well as recommendations for future studies.

Author's Contribution

The study was planned and executed by a team of researchers. The contribution of each researcher is listed below

Name	Contribution
Mr MJ Wentzel (Author)	• Designing and planning of the study; • Literature searches, interpretation of data and writing of article; • Execution of all monitoring processes; • Compiling of mini-dissertation and article.
Mr PJ Laubscher (Supervisor)	• Supervisor; • Designing and drafting of the study; • Assisted with approval of protocol, interpretation of results and documentation of the study; • Giving guidance with scientific aspects of the study; • Review of the mini-dissertation.
Mrs A van der Merwe (Co-Supervisor)	• Co-Supervisor; • Review of the mini-dissertation; • Provided guidance on scientific aspects and adding suggestions for the improvement of the mini-dissertation.

The following is a statement from the co-authors that confirms each individual's role in the study:

I declare that I have approved the above mentioned article and that my role in the study as indicated above is representative of my actual contribution and that I hereby give my consent that it may be published as part of MJ Wentzel's M.Sc in Occupational Hygiene mini-dissertation.

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Acknowledgements

I would like to express gratitude towards the following personnel at the School for Physiology, Nutrition and Consumer Services, North-West University for the opportunity to carry out this project, and for their guidance, knowledge and support.

- Mr PJ Laubscher (Supervisor)
- Mrs A Van der Merwe (Co-Supervisor)
- Prof J du Plessis (additional advisor)

I would like to thank the mining company, not only for the financing of the study, but also for the opportunity to conduct it at their facilities. I would like to thank all the personnel at the mine for their time, support, knowledge and positive attitude.

A special thanks to Ms Julize van Niekerk for her crucial assistance in the arrangement and execution of the project.

A special thanks to Dr Louwrens Tiedt of the North-West University Laboratory for Electron microscopy for his guidance and knowledge, to Dr Jaco Wentzel for proofreading this mini-dissertation, and the staff of the various monitored areas for their understanding and patience.

Abstract

Dust is a well-known occupational hygiene challenge and has been throughout the years, especially in the coal mining industry. The hazards arising from coal dust will differ between geographical areas due to the unique characteristics of dust from the coal mining environment. It is therefore of upmost importance to identify these qualities or characteristics of coal dust in order to understand the potential hazards it may pose. It is also important to consider the presence of nanoparticles which until recently remained neglected due to the absence of methods to study them.

Aim: The aim of this study was to collect significant quantities of airborne dust through static sampling to characterise the physical, morphological as well as elemental properties of inhalable and respirable dust produced at two South African underground and two opencast coal mines. Personal exposure quantification was therefore not the primary concern in this study. **Method:** Static dust sampling was done at two mining areas of the two opencast and underground coal mines using four Institute of Occupational Medicine (IOM) and four cyclone samplers per area at each mine. A condensation particle counter (CPC) was also used at the opencast areas. The opencast areas included blast hole drilling, drag line and power shovel operations. The underground areas included the continuous miner and roof bolter operations. Gravimetric analyses of the cyclone and IOM samples were done as well as scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis. **Results:** Mine A (opencast and underground) produces higher grade coal in comparison to mine B (opencast and underground). Gravimetric analysis indicated higher average inhalable (55.35 mg/m^3) and respirable (2.13 mg/m^3) concentrations of dust in the underground areas when compared to the opencast areas (34.73 mg/m^3 and 0.33 mg/m^3). Blast hole drilling operations indicated higher average inhalable and respirable dust concentrations (39.02 mg/m^3 and 0.41 mg/m^3) when compared to the drag line and power shovel operations (30.44 mg/m^3 and 0.246 mg/m^3). CPC results showed higher average concentrations of sub-micron particles at the blast hole drilling areas per cubic metre (63132 x 10^6) compared to the drag line and power shovel operations (38877 x 10^6). EDS analysis from the opencast areas indicated much higher concentrations of impurities (with lower concentrations of carbon – 33.33%) when compared to samples taken from the underground mining activities (65.41%). The EDS results from the opencast areas differed substantially. The highest concentrations of silica were found at the blast hole drilling areas. EDS results from the underground areas indicated that mine A has slightly higher concentrations of carbon (66.2%) with less impurities when compared to mine B (64.62%). The continuous miner operations showed a higher concentration of impurities when compared to the dust from the roof bolter. SEM results from the opencast areas revealed that the majority of particles are irregularly shaped and the presence of quartz and agglomerations are evident. SEM results from the underground areas were similar except that the roof bolter produced smaller sized particles when compared to the continuous miner. It also seemed that the areas with higher levels of impurities produced more sub-micron particles. **Conclusions:** It is possible to identify the majority of physical and elemental characteristics of coal dust by means of gravimetric analysis, particle counting, SEM and EDS. There were differences found, regarding the morphological; chemical and physical characteristics, between the different opencast and underground areas at mine A and mine B due to the type of mining activity and amount of overburden present. Silicosis, Pneumoconiosis and Chronic obstructive pulmonary disease are some of the possible health concerns. It has been seen that dust from higher grade coal mines contributed to more developed stages of these diseases.

Keywords:

Opencast and underground coal mining, characterisation of dust, dangers of coal dust, nanoparticles, sub-micron particles, silica.

Opsomming

Titel: *Karakterisering van luggedraagde stof in Suid-Afrikaanse ondergrond en oopgroef steenkool myne: ‘n Loods studie.*

Stof was en is steeds ‘n berugte beroepshigiëne uitdaging oor die jare, veral in die steenkool mynbedryf en sy verskeie operasies. Die gevare wat die steenkoolstof inhou sal verskil tussen verskillende geologiese areas as gevolg van die unieke eienskappe van die steenkoolstof by die verskeie myn operasies. Dit is dus van belang om die karaktereienskappe van steenkoolstof te beskryf sodat die moontlike gevare wat dit mag inhou aan die lig gebring kan word. Dit is ook belangrik om die teenwoordigheid van nanopartikels in ag te neem aangesien daar tot onlangs geen metodes was om hierdie partikels te bestudeer nie.

Doel: Die doel van hierdie studie was om genoegsame luggedraagde stof op te vang en die fisiese, morfologiese en chemiese eienskappe van die stof afkomstig van twee Suid-Afrikaanse ondergrondse en oopgroef steenkool myne te karakteriseer. Persoonlike monsterneming vir persoonlike blootstelling kwantifisering was dus nie die doel van die studie nie. **Metode:** Area monitoring is onderneem by twee areas van beide die twee oopgroef en ondergrondse steenkool myne deur gebruik te maak van vier IOM en vier Sikloon stof monsternemers per area, sowel as ‘n kondensasie partikel teller (CPC) by die oopgroef areas. Die oopgroef areas het “*blast hole drilling*”, “*drag line*” en “*power shovel*” operasies ingesluit. Die ondergrondse areas het “*continuous miner*” en “*roof bolter*” operasies ingesluit. Gravimetriese analises van die stof monsters is gedoen sowel as skandering elektronmikroskopie (SEM) en energie verspreiding X-straal-spektroskopie (EDS) analises. **Resultate:** Gravimetriese analises het hoër inasembare (55.35 mg/m^3) en respireerbare stof (2.13 mg/m^3) konsentrasies by die ondergrondse areas aangedui in vergelyking met die oopgroef areas (34.73 mg/m^3 en 0.33 mg/m^3). “*Blast hole drilling*” operasies het ook hoër inasembare en respireerbare stof konsentrasies (39.02 mg/m^3 en 0.41 mg/m^3) getoon in vergelyking met die “*drag line*” en “*power shovel*” operasies (30.44 mg/m^3 en 0.246 mg/m^3). CPC resultate het hoër konsentrasies sub-mikron partikels aangedui by die “*Blast hole drilling*” areas (63132 x 10^6) in vergelyking met die “*drag line*” en *power shovel*” operasies (38877 x 10^6). EDS analises het baie hoër konsentrasies van onsuiwerhede (met laer konsentrasies van koolstof - 33.33%) by die oopgroef areas aangedui in vergelyking met die ondergrondse aktiwiteite (65.41%). Die EDS resultate van die oopgroef areas het ook baie van mekaar verskil. Die hoogste konsentrasies van silika is gevind by die boor areas. EDS resultate van die ondergrondse areas het aangedui dat myn A hoër konsentrasies van het (66.2%) in vergelyking met myn B (64.62%). Die stof van die “*continuous miner*” operasies het hoër konsentrasies van onsuiwerhede as die “*roof bolter*” operasies aangedui. Die SEM resultate van die oopgroef areas het aangedui dat die meerderheid van die partikels oneweredige vorms het en die teenwoordigheid van kwarts en agglomerulasies is duidelik sigbaar. SEM resultate van die ondergrondse areas is baie eenders behalwe vir die “*roof bolter*” areas wat kleiner partikels as die “*continuous miner*” areas geproduseer het. Dit het ook geblyk dat die areas met hoër konsentrasies van onsuiwerhede stof geproduseer het met meer sub-mikron partikels. **Gevolgtrekking:** Dit is moontlik om die meerderheid van die fisiese en chemise eienskappe van steenkoolstof te identifiseer deur gebruik te maak van gravimetriese analises, sowel as verbeterde metodes naamlik skandering elektronmikroskopie (SEM) en energie verspreiding X-straal-spektroskopie (EDS) analises. Daar was verskille gevind tussen die morfologiese, fisiese en chemise eienskappe van die verskillende oopgroef en ondergrondse areas van myn A en myn B. Die hoof redes hiervoor is as gevolg van die tipe myn aktiwiteite sowel as die hoeveelheid bolaag teenwoordig by die spesifieke areas van belang. Silikose, pneumokoniosis en kroniese obstruktiewe pulmonêre siektes is van die moontlike gesondheidsgevare. Dit is reeds gevind dat stof van hoër graad steenkool myne bydra tot meer gevorderde stadiums van hierdie siektes.

Sleutelwoorde:

Oopgroef en ondergrondse steenkool myne, karakterisering van stof, gevare van steenkool stof, nanopartikels, sub-mikron partikels, silika.

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List of Symbols and Abbreviations

Symbols

%	Percentage
σ	90th percentile
µg/g	Microgram per gram
µm	Micrometre
Al	Aluminium
$(Al_2Si_2O_5(OH)_4)$	Kaolinite
C	Carbon
Ca	Calcium
$CaCO_3$	Calcite
$(CaMg)(CO_3)_2$	Dolomite
Cu	Copper
Fe	Iron
FeO	Iron oxide
$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$	Illite
L/min	Litre per minute
mg	Milligram
mg/m^3	Milligram per cubic meter
m^3	Cubic metre
Mg	Magnesium
nm	Nanometre
O_2	Oxygen
S	Sulphur
SiO_2	Silica dioxide

Abbreviations

CPC	Condensation particle counter
CWP	Coal workers’ pneumoconiosis
DLPI	Dekati low pressure impactor
EDS	Energy dispersive X-ray spectroscopy
EUR	European Commission
HSDB	Hazardous substances data bank
IOM	Institute of Occupational Medicine
ISO	International Organization for Standardization
MDHS	Methods for the Determination of Hazardous Substances
MHS	Mine Health and Safety
NIOSH	National Institute for Occupational Safety and Health
OEL	Occupational exposure limit
PMF	Progressive massive fibrosis
PNOC	Particles not otherwise classified
SEM	Scanning electron microscope
WHO	World Health Organization

CHAPTER 1

INTRODUCTION

1.1 Overview

Over the last three hundred years, coal has played a central role in the production of energy. The industrial revolution would have been impossible without this fossil fuel powering steam engines and iron forges (Wringley, 1962). Even today coal is still widely used as the primary source of energy production and the coal mining industry will remain a big role player in the economic sector for years to come (Finkelman *et al.,* 2002). It is well known that dust has been one of the largest occupational dangers through the years (Petavratzi *et al.,* 2005) and the coal mining industry is plagued with potential hazards arising from the dust produced at its different operations. Some of these hazards include coal dust explosions as well as a vast range of hazardous health effects such as silicosis and coal workers pneumoconiosis. There is very little literature available about the characterisation of dust or differences in dust characteristics between different mining activities (Wallace *et al.,* 1990; Grayson, 1991). It is impossible to fully comprehend all the possible dangers to human health coal dust may have by mere inhalable, respirable and particle size distribution analysis. In many cases it is blindly accepted that dust from different areas at the same type of mine is similar. It is essential to indicate the particle size, particle size distribution and morphological shape as well as elemental composition when investigating dust exposures (Arup Environmental, 1995). It is thus extremely important to identify all the characteristics of coal dust, which has never been done in detail, to better understand all the potential health hazards it may hold. With the advancements in analytical methods and instrumentation, it is now possible to characterise dust more fully by means of electron microscopy (SEM), energy dispersive X-ray spectroscopy (EDS) analysis and particle counting apparatuses which are capable of identifying ultrafine particles.

The two main methods for mining coal are opencast and underground mining (Energy Information Administration, 1994). There are many areas on site that produce large amounts of dust at both these types of mines. The areas at an opencast mine will include drilling, drag line and power shovel operations. The areas producing the most dust at an underground coal mine will include the roof bolter and continuous miner operations. To identify the unique qualities of the dust produced at each of these areas it is important to study its morphological, physical and chemical characteristics (Arup Environmental, 1995). The morphological characterisation will include its size, shape and distribution of the dust as well as the identification of submicron particles. Nanoparticles especially raised specialized health concerns during the past few years (Biswas and Wu, 2005). The chemical characteristics will include the elemental and mineral composition of the coal dust.

The aim of this project was to conduct a pilot characterisation study of coal dust. For this pilot study two Coal mines were selected, both of which have opencast and underground mining activities. Mine A produces higher grade coal for exporting purposes and mine B produces lower grade coal for energy production. Because this is a descriptive pilot study the purpose of the sampling was only to collect enough airborne dust on the filters for SEM and EDS analysis. It was decided to collect static samples in areas of high dust concentrations that were cited by the mine's Occupational Hygienist. Both respiratory and inhalable sampling was done at the same areas during the same time. This also applies for the identification of sub-micron particles. The sampling areas identified at the opencast mines were the blast hole drilling site as well as the drag line and power shovel operations. The sampling areas identified in the underground mines were at the roof bolting and continuous miner operations. All the samples were taken under normal working conditions.

The research objectives were:

1) To collect enough airborne dust per sample to be able to transfer adequate dust to the SEM stubs for analysis.
2) To characterise the dust chemically and physically by means of electron microscopy, energy dispersive X-ray spectroscopy and particle size analysis.
3) To compare the characteristics of dust derived from high and low grade coal as well as different mining activities.

1.2 Problem Statement

Dust sampling of various fractions in the mining environment has become a crucial part of controlling personal exposure to dust (Seixas *et al*., 1995). Traditionally dust is characterised by means of gravimetric analysis of inhalable and respirable fractions as well as super-micron particle size distribution. The amount of published literature available on the full characterisation (physical, elemental as well as sub-micron particle size distribution) of dust and especially coal dust is very limited (Wallace *et al*., 1990; Grayson, 1991).

To gain sufficient knowledge of possible unidentified health risks to exposure of coal dust at different types of mines and mining operations, it is of utmost importance to launch a descriptive pilot study to identify possible hereto unidentified factors by physical and chemical characterisation of airborne mining dust.

Due to more advanced methods and technologies available it is now possible to evaluate the morphology of dust by means of electron microscopy (SEM), analyze that same sample used for electron microscopy chemically with the use of energy dispersive X-ray spectroscopy (EDS) and measure sub-micron size distribution of dust particles. This could create an awareness of the need that new methods are necessary in the evaluation of the exposure to dust of mine workers.

1.3 Hypothesis

1) The characteristics of dust formed during different types of coal mining operations can be identified by means of gravimetrical analysis, SEM and EDS and will differ in composition, shape of the particles and size distribution.
2) The characteristics of respirable and inhalable dust formed in mines where high grade coal is mined, differs from that where low grade coal are mined.

1.4 References

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CHAPTER 2

LITERATURE STUDY

2.1 Introduction

Coal is one of the world's leading sources for the production of energy and the coal mining industry is growing continuously. This is evident in South Africa where there are 65 coal mines in the Mpumalanga Province alone. Coal will most likely also be the dominant energy source in developing countries for at least the first half of the 21st century (Wringley, 1962; Finkelman *et al.,* 2002). There are many hazards this mining industry faces and one of the biggest dangers is coal dust. Dust in general has a hazardous potential towards human health, the environment as well as the productivity of a mine (Tilbury *et al.,* 2005). These particulate emissions can be produced by a variety of mining activities. Particulates associated with mining activities usually originate from the disturbance of fine particles derived from rock and soil. Dust associated with mining activities is typically less complex in its composition, consisting mainly of particles from exposed soil and rock (Petavratzi *et al.,* 2005).

Dust is the term used to describe fine particles that are suspended in the atmosphere and that normally have diameters below 100 µm. Dust may have adverse impacts on the environment, human health as well as productivity (Petavratzi *et al.,* 2005). Agriculture and the ecology are the main victims when it comes to the environmental effects of dust. There is also a wide range of possible adverse health effects when exposed to dust. Examples include lung damage, damage to the nose, throat and eyes, damage to the skin, systemic poisoning, gastrointestinal tract irritation, ischaemic heart diseases, inflammatory lung diseases, allergic reactions as well as carcinogenic effects (World Health Organization, 1999). Safety and productivity can also be adversely influenced by dust. Certain dusts from sulphide and coal ores are explosive and hold a strong safety risk. Dust can also cause product damage and may shorten the life cycle of equipment (Soundararajan *et al.,* 1996).

It is well known that dust has been one of the largest occupational challenges through the years (Petavratzi *et al*., 2005), but it is important to realise that the potential hazardous effects of dust differs between different geographical areas. For example the dust produced at an American coal mine, or even another South African coal mine, will not be exactly the same as that produced at a specific South African coal mine. The dust may differ in particulate size, trace elements and general composition. All of these factors will influence the possible health effects (Buzea *et al*., 2007). Another important factor is the presence of nanoparticles within the dust. A number of resent studies show the importance of understanding these nanoparticles and it is believed that nanoparticles induce more severe health effects than larger particles (DunXi *et al*., 2009). The lack of studies and literature concerning characterisation of dust, and especially coal dust, limits our understanding of all the potential hazards it may hold. Without the characterizing of dust and all its aspects, it will be impossible to understand the health risks adequately.

Opencast and underground coal mining

The two main methods for mining coal are opencast and underground mining (Finkelman *et al.,* 2002). The most economical method for coal mining or coal extraction from coal seams largely depends on the quality and depth of the coal seam as well as geological and environmental factors. The choice of extraction method is primarily influenced on the depth of the seam, density of the overburden and thickness of the coal seam (Energy Information Administration, 1994). Seams that are relatively close to the surface (approximately 50 m) are usually mined using opencast mining. Coal seams that occur at depths of between 50 m and 100 m are usually deep mined (underground mining).

2.1.1 Opencast coal mining

When coal seams are near the surface it will be more economical to extract the coal using opencast mining methods. Opencast mining recovers a greater proportion of coal than underground mining because more of the coal seam can be exploited (Scott *et al.*, 2010).

The first step in opencast mining will be the removal of topsoil and the flora of the mining area by means of bulldozing. The rock and soil covering the coal seam are known as overburden. The second step will be to get rid of this overburden by means of drilling and blasting to loosen this layer. The overburden is then removed by draglines or power shovels and transported to the overburden dumping sites. Once the coal seam is exposed, it will be drilled, fractured by means of explosives and then systematically mined in strips (see figure 1 for summary of opencast mining process). The coal will then be loaded for transport to either the coal preparation plant or direct to where it will be used (Scott *et al.*, 2010).

The areas at an opencast coal mine identified to produce the most dust are the following:

Blast hole drilling operations

Self-propelled crawler-mounted electric blast hole drilling rig is designed for drilling vertical and inclined holes at opencast mining (Altindag, 2003). The drilling rig provides drilling of holes with 160-215 mm in diameter and 40 m in depth. Explosive charges are then placed in these holes and detonated to loosen the overburden and fracture the coal seams.

Drag line operations

The dragline mining system is a combination of overburden removing, hauling and dumping. Due to simplicity of operation it is known as a low-cost process. Draglines are used for opencast mining of mineral resources with no handling facilities and also during construction of the canals, irrigation and various water-development projects. Draglines are intended to excavate soils of up to the 4th category of hardness inclusive. In this case the soils of the 3rd and 4th category are to be preliminarily loosened by blasting (Zhou *et al.,* 2007).

Power shovel operations

Power shovels are the main stripping and mining machines. These shovels are designed to mine rocks with the volume weight in the pillar being no more than 2800 kg/m^3 and provide damping of the material both on trucks and to the spoil bank (Ghose and Majee, 2000).

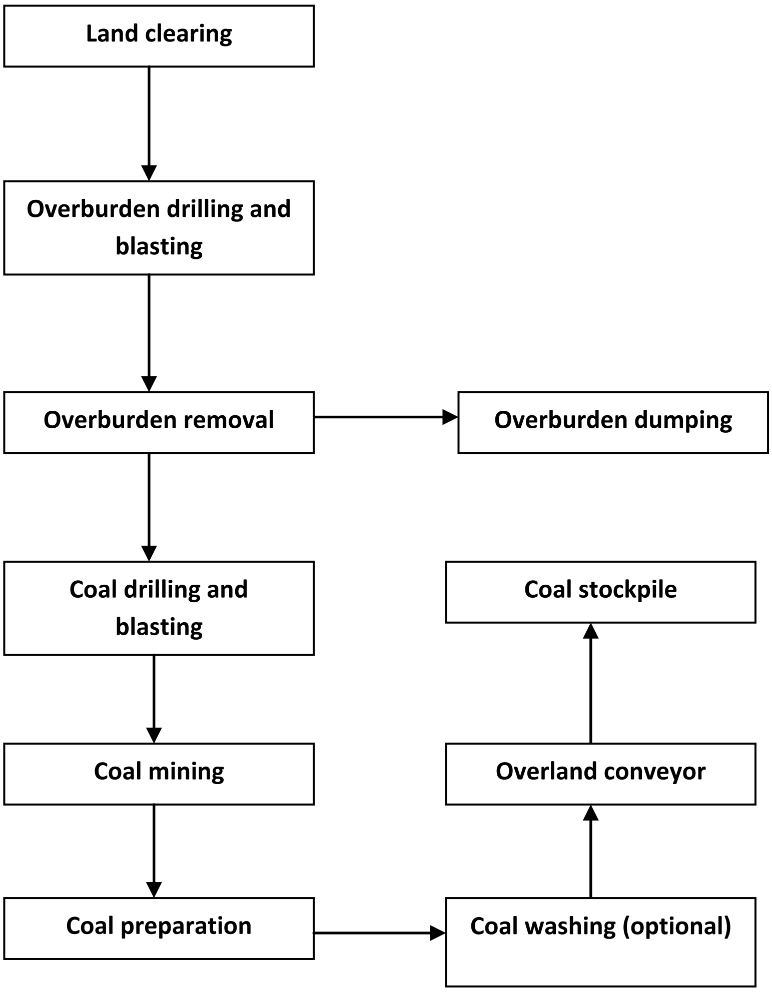

Figure 1: Summary of the opencast coal mining process.

2.1.2 Underground coal mining

Most coal seams are too deep for opencast mining and require underground extraction. Underground mining currently accounts for 60% of the world's coal production. In underground mining there are two main methods of mining namely "room and pillar" and long wall mining. In "room and pillar" mining, coal deposits are mined by cutting a network of 'rooms' into the coal seam with a Continuous Miner machine and leaving behind 'pillars' of coal to support the roof of the mine. Once this mining method becomes too difficult to continue due to geology or ventilation a supplementary mining method is used termed second mining or retreat mining where the coal from the pillars are removed causing the mine to collapse section by section (Energy Information Administration, 1994).

Continuous mining utilizes a continuous miner machine with a large rotating steel drum with tungsten carbide teeth that scrape coal from the seam. This machine operates in a room and pillar system where the mine is divided into a series of 5 to 10 m^2 rooms. This machine can mine up to five tons of coal per minute and accounts for 45% of underground coal production in the world. After 12 meters of mining the continuous miner pulls out and the roof is then supported by a roof bolter. The mining face is then serviced after which the continuous miner can advance again (see figure 2.1 and 2.2 for summary of underground mining process).

The areas at an opencast coal mine identified to produce the most dust are the following:

Continuous miner operations

As stated above a continuous miner machine has a large rotating steel drum equipped with tungsten carbide teeth that scrape coal from the seam. This machine operates in a "room and pillar" system, where the mine is divided into a series of work areas cut into the coal bed (Scott *et al.*, 2010).

Roof bolter operations

A roof bolter is a hydraulically driven miner-mounted bolting rig used to install rock bolts in mines, tunnels, underground power plants and storage facilities. Roof bolting is also a common application in underground coal mines for securing mine roofs to be self-supportive. It is extremely dangerous as an occupation, accounting for nearly 56 percent of injuries in underground coal mining operations.

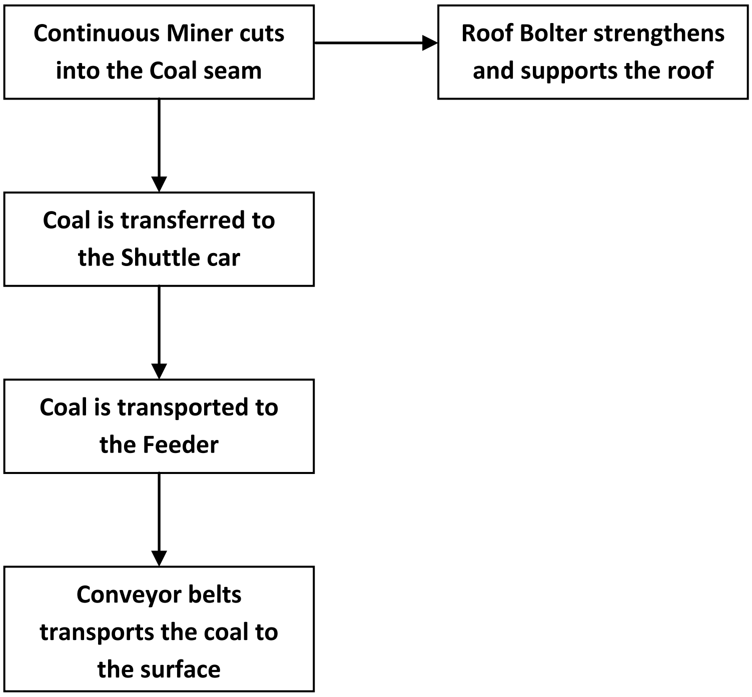

Figure 2.1: Summary of the underground coal mining process.

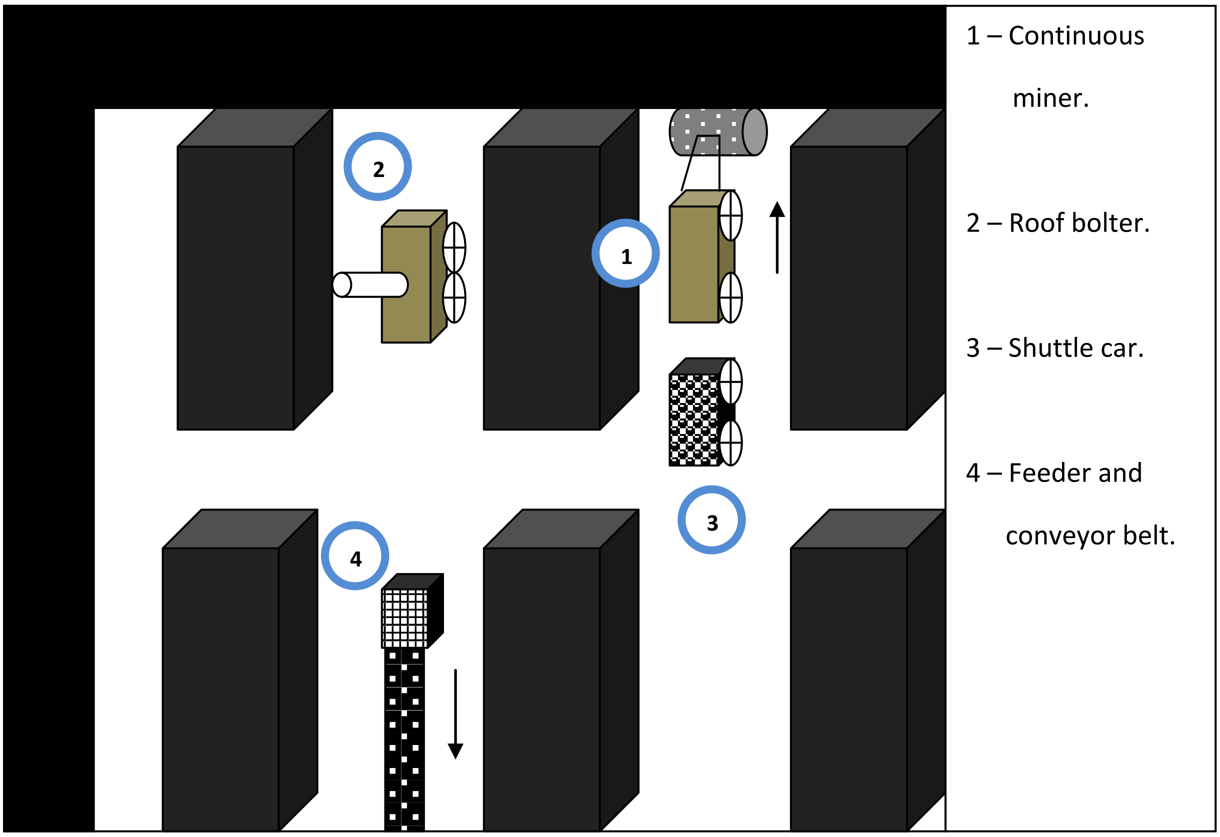

Figure 2.2: Diagrammatic illustration of the underground coal mining process.

2.2 Generation of dust

Dust usually originates from larger masses of the same material, caused by different mechanical breakdown processes. In mineral mining sites dust is usually generated during excavation, transportation and mineral processing operations. Dust generation is influenced by material properties, such as hardness, particle size distribution, particle density and moisture. Process parameters such as mechanical breakdown, energy spent on the process, drop from heights, solid mass flow rate and the extent of handling also plays a role in the amount of possible dust generation (World Health Organization, 1999). The composition of generated dust is not necessarily the same as that of a parent rock since different minerals might break down or be removed at different rates.

2.3 Characteristics of dust

The behaviour of dust particles in air is quite complex as it consists of different forces acting on different sized dust particles. For a particle to become airborne it must have an aerodynamic drag force larger than the sum of the particle weight and the interparticle forces (Liu, 2003). Smaller particles on the other hand will behave as a gas and will be influenced by molecular forces. Gravitational and inertial forces will play a bigger role in the behaviour of larger particles when compared to smaller particles (SIMRAC, 2003).

The main forces influencing emitted dust particles are gravitational settlement, Brownian motion, Eddy diffusion and agglomeration. Other mechanisms like impaction, re-entrainment and deposition, are also important. The gravitational forces will cause the dust particles to settle under its own weight (SIMRAC, 2003).

The relentless bombardment of gas molecules against suspended dust particles may cause that these particles will follow irregular paths even in still air. This type of behaviour, termed Brownian motion is very important for particles smaller than 0.6 µm where the gravitational settlement can be assumed negligible (SIMRAC, 2003). Brownian motion is the presumably random moving of particles suspended in gas or liquid form resulting from their bombardment by the fast-moving atoms or molecules in the gas (Mörtes and Peres, 2008).

Eddy diffusion is mostly present in ventilating air and is caused due to turbulence. Eddy diffusion (also termed turbulent diffusion) is any diffusion process by which substances are mixed in the atmosphere or in any fluid system due to the turbulence (Mörtes and Peres, 2008). Agglomeration is the result of particles colliding with each other due to their motion and then adheres to form larger particles. It is considered that agglomeration is the most important interparticle phenomenon for airborne particles. Impaction is the result of the inertia of a particle at higher velocities impacting onto an object and adhering to it and then re-entraining into the air (SIMRAC, 2003).

Dust deposition will also depend upon the prevalent weather conditions, as well as the particle size. The wind can transport suspended particles over a wide area. Smaller particles will remain suspended for longer periods, dispersing widely and depositing more slowly. Larger dust particles will be deposited more quickly. Particles over 30 µm make up the greater proportion of dust emitted from mining activities and will deposit within 100 m of the source. Intermediate sized particles (10–30 µm) will be able to travel up to 200–500 m. Particles smaller than 10 µm represent a small portion of dust emitted from most mining activities and are deposited slowly (Petavratzi *et al.,* 2005).

There are very few studies done describing the characterisation of certain aspects of dust and even fewer studies on the total characterisation of dust. It was only during the past few years that attention has been drawn to the importance of particle analysis for a full characterisation of dust and especially respirable dust (Wallace *et al.,* 1990; Grayson, 1991; Probert *et al.,* 1994). To be able to classify and evaluate dust exposures it will be necessary to identify its physical properties, its chemical properties as well as its composition. Particle size, shape, chemical composition and mass concentration are important parameters for characterizing the behaviour of dust (Arup Environmental, 1995). The physical properties of dust include its size and distribution as well as its surface area and shape.

2.3.1 Size Distribution

The size distribution describes the number of the different sized particles in a specific volume of air. The distribution of dust particles can be identified by means of gravimetrical analysis as well as direct reading instruments. Gravimetrical analysis is done by drawing a known amount of air, containing dust particles, through different filter media that are designed to capture certain sized particles. With this method it is possible to capture particles smaller than 100 µm in diameter as well as particles smaller than 10 µm depending on the type of sampler that is used. The concentration of different sized particles can then be calculated and the distribution of dust particles in a known amount of air identified. There are also direct reading instruments capable of measuring the amount of airborne particles between certain size ranges. These instruments also draw a known amount of air and calculate the distribution of different sized particles. A condensation particle counter (CPC) is used to measure the particle number concentration down to the nanometre size range (between 0.01 µm and 1 µm). The lower detection efficiency of CPC’s is much lower than in optical particle counters. The particles are enlarged due to super saturation and a subsequent condensation of a condensable gas. The particles then reach a size at which they can be optically detected.

2.3.2 Size

Dust particles are normally classified into inhalable (smaller than 100 µm), thoracic (smaller than 10 µm) and respirable (smaller than 4µm) dust (Oberdörster, 2001). The size of dust particles can be determined by means of gravimetric sampling combined with direct reading instruments. The drawback of these methods is that they only give average results without indicating the precise size of the captured dust particles. This is where a scanning electron microscope (SEM) can be used to great advantage. The SEM is capable of determining the size of particles down to 0.01 µm in diameter. The SEM is also capable of viewing nanoparticles (smaller than 0.01 µm in diameter). A dust sample can be sputter coated with gold/palladium making the sub-micron particles more visible when viewed under the SEM.
Sputter coating in scanning electron microscopy is the process of covering a specimen with a thin layer of conducting material, typically a metal, such as a gold/palladium (Au/Pd) alloy. A conductive coating is needed to prevent charging of a specimen with an electron beam in conventional SEM mode (high vacuum, high voltage) (Newbery*,* 1986).

2.3.3 Surface area

The surface area and shape of the particle will influence the manner in which it will or can react with other materials for example lung tissue. The surface area and shape of different sized particles can also be determined by means of a scanning electron microscope. This information is important to determine where the particles will be deposited in the lungs and the probable reactivity it may have (Oberdörster, 2001).

Dust particles are mostly composed of different materials and these particles are often agglomerations with various compositions (Buzea *et al.,* 2007). There are several factors to consider when looking at the composition and properties of dust. For example the presence of metals, metal oxides, carbon, it’s purity etc. There are many possible trace elements in coal dust that could be hazardous to human health for example arsenic, fluorine, mercury, selenium, silica, nickel, aluminium and iron (Finkelman *et al.,* 2002). Identifying the elemental composition of dust can be done by means of SEM combined with energy dispersive X-ray spectroscopy (EDS). EDS is a relatively simple yet powerful technique used to identify the elemental composition of as little as a cubic micron of material. The equipment is attached to the SEM to allow for elemental information to be gathered about the sample under investigation (Reddy *et al.,* 2000). Recently, the combined scanning electron microscopy (SEM)/energy-dispersive X-ray spectroscopy (EDS) microanalysis has been developed as an elegant and powerful tool to obtain information regarding the morphology and textural properties of materials. Information regarding interparticle interactions, crystal growth, alloy formation, etc., has been obtained successfully by exploiting this technique (Huang *et al.,* 1996).

2.3.4 Composition of coal dust

Coal dust is mostly composed of the following minerals:

- Calcite ($CaCO_3$) which is a carbonate mineral.
- Dolomite ($(CaMg)(CO_3)_2$) which is a carbonate mineral.
- Quartz (SiO_2) which is a silicate mineral.
- Kaolinite ($Al_2Si_2O_5(OH)_4$) which is a silicate mineral.
- Illite ($(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$).
- Carbonaceous material (Rainey *et al.,* 1994).

The highest concentrations of minerals found in coal dust will be Quartz, Kaolinite and Illite (Jones *et al.,* 2002).

2.3.4.1 Quartz

Quartz is the second most abundant mineral in the earth's continental crust and is a frequently occurring solid component of most natural mineral dust (Rice, 2000). It is made up of a continuous framework of SiO_4, with each oxygen being shared between two tetrahedral, giving an overall formula SiO_2. Quartz is an extremely hard mineral and scores 7 out of 10 on the Mohs scale that measures material hardness. When quartz fractures it shows a conchoidal fracture that is very similar to that of glass with very uneven and sharp edges. Even though quartz is very hard, it is also quite brittle and easily shattered into smaller pieces with enough power for example during the drilling process at coal mines. Human exposures to quartz occur most often during occupational activities that involve movement of earth, disturbance of silica-containing products, or use or manufacture of silica-containing products. Inhalable and respirable silica or quartz is associated with respiratory diseases like silicosis, the formation of Reactive Oxygen Species (ROS), tumour formation and finally cancer (Hendryx and Ahern, 2008).

2.3.4.2 Kaolinite

Kaolinite is a clay mineral and forms part of a group of industrial minerals. It is a layered silicate mineral with the chemical composition $Al_2Si_2O_5(OH)_4$. Rocks that are rich in kaolinite are known as kaolin or china clay. Kaolinite is a soft mineral produced by the chemical weathering of aluminium silicate minerals like feldspar (which is the most commonly found mineral on the planet). This mineral is rarely found in crystal form and microscopic images will indicate that kaolinite will have plate or clusters of plate structures (Altekruze *et al.,* 1984). The accumulation of these particles in the lungs may lead to koalinosis (kaolin pneumoconiosis) and cumulative lung damage (Rainey *et al.,* 1994).

2.3.4.3 Illite

Illite is a clay sized micaceous mineral that is part of the clay minerals and commonly found in sedimentary rocks and especially shales. It can also be described as a layered alumino-silicate with the chemical formula $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$ (Merriman and Frey, 1999). Illite, a phyllosilicate, has a poor crystallinity, a size of less than 2 µm, and a crystal structure similar to muscovite. It is widespread in many geological settings of the Earth’s crust, such as diagenesis in mudrocks, very low grade metamorphism and hydrothermal systems. Illite however is mostly found in near-surface and relatively shallow geologic environments (Chen *et al.,* 2013). The accumulation of these particles in the lungs may also lead to cumulative lung damage as most clay minerals would. Pulmonary fibrosis and silicosis are the major concern where illite is concerned.

These minerals will make out the majority of impurities found in dust and especially coal dust. The purity of coal dust will be determined by the amount of carbon compared to the amount of other elements or minerals found in the coal dust. Areas where the purity of coal dust is expected to be higher are the underground mining areas where the carbon is much more densely packed over the millennia to form the coal riffs. Coal mining activities where there will be a much larger percentage of impurities will be the opencast areas. Because of the surface soil (or overburden), which is mostly composed of the above mentioned minerals, the amount of impurities will be much higher. This will not be true for all the opencast areas however. At the early stages of opencast mining there will be a lot more surface soil present and thus a lot more impurities found in the coal dust. As the mining process progresses the coal riff will finally be reached and the mining activities during this phase will produce dust that will contain much less impurities and a higher percentage of carbon. Phillips and Belle (2003) believe that the surrounding minerals (present in the overburden covering the coal seam) at coal mines with higher grade coal, may contain higher concentrations of silica.

Aside from the different mining areas, the specific mining activity will also play a role in the composition and size of the coal dust. Certain minerals are more brittle than others and tend to break into smaller fractions more easily without much effort. Other minerals like quartz are much harder and mining activities such as blast hole drilling and roof bolting will crush this mineral into much smaller pieces making it more prone to become airborne. Other studies have also shown that grinding and drilling activities yields respirable dust generation rates that increase with coal rank (Moore and Bise, 1984; Srikanth *et al*., 1995), in other words, the higher the carbon concentration (coal rank) at a coal mine, the more respirable dust is generated.

Thus the composition of coal dust will not only be influenced by the mining area, but also by the specific mining activity in that area. Determining the composition is a crucial part in dust characterisation and identification of possible health effects.

2.4 Dangers of coal dust

2.4.1 Coal dust explosions

For a dust explosion to occur the following requirements must be met:

- It must be a combustible dust;
- it must be dispersed in air;
- the concentration must be above the flammable limit;
- a sufficient ignition source must be present;
- confinement of the dust-air mixture (Cashdollar, 2000).

Coal dust in suspended concentrations of 50 000 mg/m^3 and higher are capable of being ignited. This represents the minimum explosive concentration. The minimum energy required to ignite a cloud of coal dust is 0.03 Joules which is about 100 times as much energy as is required to ignite a methane/air mixture. Coal dust suspended in air will ignite at temperatures as low as 440 ºC (Cain, 2003). By comparison, the minimum ignition temperature of a layer of coal dust is roughly 180 ºC. It was suggested that the size of coal dust particles that would contribute to a coal dust explosion must be smaller than 240 µm. This will also indicate that the finer the dust, the more danger it presents. To combat the possibility of coal dust explosions, the method of stone dusting was introduced in the early 20th century. During a coal dust or methane explosion the pressure wave can dislodge coal dust from the sides and roof of the mine tunnels leading to a chain reaction of explosions. The stone dust, which are mostly composed of calcium and other incombustible substances, will dilute the coal dust and prevent further explosion (Cain, 2003).

2.4.2 Health effects:

Silicosis

Many industries have reported that there are occupational exposures to respirable quartz but the coal mining industry has been associated with some of the highest exposures to respirable quartz. Due to this fact, silicosis is one of the biggest health concerns at coal mines and remains a significant cause of morbidity and mortality (American Thoracic Society, 1997). Silicosis (also known as nodular pulmonary fibrosis) is a fibrotic disease of the lungs produced by the inhalation and deposition of dust containing damaging amounts of respirable free crystalline silica or silicon dioxide (see figure 3 for mechanism of carcinogenicity). Although acute silicosis is a possibility under conditions of intense exposure, the most common form encountered is the chronic form, which takes many years of exposure to develop. There are three types of silicosis that a worker may develop, depending on the airborne concentration of respirable crystalline silica: (a) chronic silicosis, which usually occurs after 10 or more years of exposure at relatively low concentrations; (b) accelerated silicosis, which develops 5 to10 years after the first exposure; or (c) acute silicosis, which develops after exposure to high concentrations of respirable crystalline silica and results in symptoms within a few weeks to 5 years after the initial exposure (Ziskind *et al.,* 1976; Peters, 1986; NIOSH, 1992).

Silicosis has frequently been associated with mycobacterium as silica increases the risk of contracting tuberculosis (Peters, 1986). The association between tuberculosis and silicosis has been firmly established by the results of epidemiological studies conducted during this century (Balmes, 1990). In recent studies of silicotics, the association was well supported by the results of a survey of tuberculosis deaths among silicotics in the USA (Althouse *et al*., 1995).

Pneumoconiosis

There is a clear similarity between the pathological appearances and behaviour of pneumoconiosis whether it is because of coal or other carbonaceous material. The terms coal workers' pneumoconiosis (CWP) and progressive massive fibrosis have been used to describe the lesions. Coal workers' pneumoconiosis refers to small, discrete macules (macula means a stain or spot) or nodules not larger than approximately 10 mm in diameter. Progressive massive fibrosis (PMF) on the other hand describes confluent masses of dust and collagen fibrosis more than 1 cm in diameter (Parkes, 1994). Huang *et al.* (1996) suggest that acid-soluble ferrous iron probably derived from pyrite may be the principal lung irritant leading to Coal Workers' Pneumoconiosis (black lung disease). The presence of calcite in the coal dust may help to neutralize the acid and reduce or prevent the respiratory problem. The risk for CWP depends on the total dust burden in the lungs and is also related to the coal rank, which is based on its carbon content. In the higher ranking coal, there may be a greater relative surface area of the coal dust particles, higher surface-free radicals and higher silica content which will increase the chances of contraction CWP and Silicosis (Organiscak and Page, 1999; Phillips and Belle, 2003).

Chronic obstructive pulmonary disease

The potential of coal mine dust to cause damaging pneumoconiosis has long been recognized, but resent research suggested that pneumoconiosis is not the only respiratory hazard in the coal mining environment. Over the last 30 years evidence has accumulated that coal miners also experience an excess of chronic obstructive pulmonary disease (Coggan and Taylor, 1998). Chronic obstructive pulmonary disease (COPD) is a disease state characterised by airflow limitation that is not fully reversible. The airflow limitation is usually both progressive and associated with an abnormal inflammatory response of the lungs to noxious particles and gases (Boschetto *et al.*, 2006). Occupational exposure to respirable silica dust is associated with chronic obstructive pulmonary disease, including bronchitis and emphysema. Although these health effects are mostly associated with smoking, some epidemiological studies suggested that they may be present to a significant extent in non-smokers with occupational exposure to quartz (Kreiss *et al.,* 1989; Cowie and Mabena, 1991).

Epidemiologic studies have reported causal relationships between exposures to high concentrations of ambient air particles and increased morbidity in individuals with underlying respiratory problems. Polymorphonuclear leukocytes (PMN) are frequently present in the airways of individuals exposed to particles. Upon particulate stimulation the PMN may release reactive oxygen species (ROS), which can result in tissue damage and injury (Prahalad *et al.,* 1999). Reactive oxygen species are known to promote tumour formation within the respiratory tract (Hansen and Mossman, 1987). The immune activation by occupational exposure to respirable quartz may be linked to scleroderma, rheumatoid arthritis, polyarthritis, mixed connective tissue disease, systemic lupus erythematosus, Sjögren's syndrome, polymyositis, and fibrositis (Ziegler and Haustein, 1992; Otsuki *et al.,* 1998). The mechanism that leads to autoimmune diseases after quartz dust exposure is not yet known (Otsuki *et al*., 1998). One theory is that when respirable silica particles are encapsulated by macrophages, fibrogenic proteins and growth factors are generated that ultimately activates the immune system (Ziegler and Haustein, 1992)

More recent studies indicated that the lungs do have mechanisms to defend against intruder particles for example the displacement of particles into the surface lining layer in the small airways and alveoli. These particles are then brought to the macrophage cells which are the largest clearance system in the peripheral lung. However, the displacement of particles toward the epithelial cells facilitates the interaction of the particles or any parts of them with many other lung cells, which may have consequences for lung disease. The microscopic analyses of inhaled and deposited particles in intrapulmonary conducting airways and in alveoli revealed that, regardless of the anatomical site and particle nature, all of the particles were submersed in the aqueous lining layer or coated by the lining film material (Geiser *et al*., 2002). Other studies also indicated that when the same gravimetric doses of ultrafine and fine particles were delivered to the lung, ultrafine particles produced significantly greater inflammation and interstitial translocation (Ferin *et al.*,1991; Oberdörster *et al.,* 1992). These studies also showed that the pulmonary clearance of the ultrafine particles were significantly slower when compared to the clearance of the fine particles (Oberdörster *et al.,* 1994). Exposure to particulate silica (most crystalline polymorphs) causes a persistent inflammation sustained by the release of oxidants in the alveolar space. Reactive oxygen species (ROS), which include hydroxyl radical, superoxide anion, hydrogen peroxide, and singlet oxygen, are generated not only at the particle surface, but also by phagocytic cells attempting to digest the silica particle (Fubini and Hubbard, 2003).

Lung macrophages may not be able to transport particular types of particles out of the lungs. One proposed mechanism is that the dust particles cause the macrophage to generate enzymes that eventually lead to its destruction and the formation of abnormal tissue in the lung**,** although one of the normal mechanisms for the elimination of foreign particles relies on the capability of macrophages to dissolve solid particles of low aqueous solubility (Berry *et* *al*., 1978; Berry *et al*., 1982; Kreyling, 1992) recent studies have shown that the opposite can also occur where the lysosome of lung macrophages may concentrate and precipitate elements inhaled as a part of water soluble compounds (Galle *et al*., 1992).

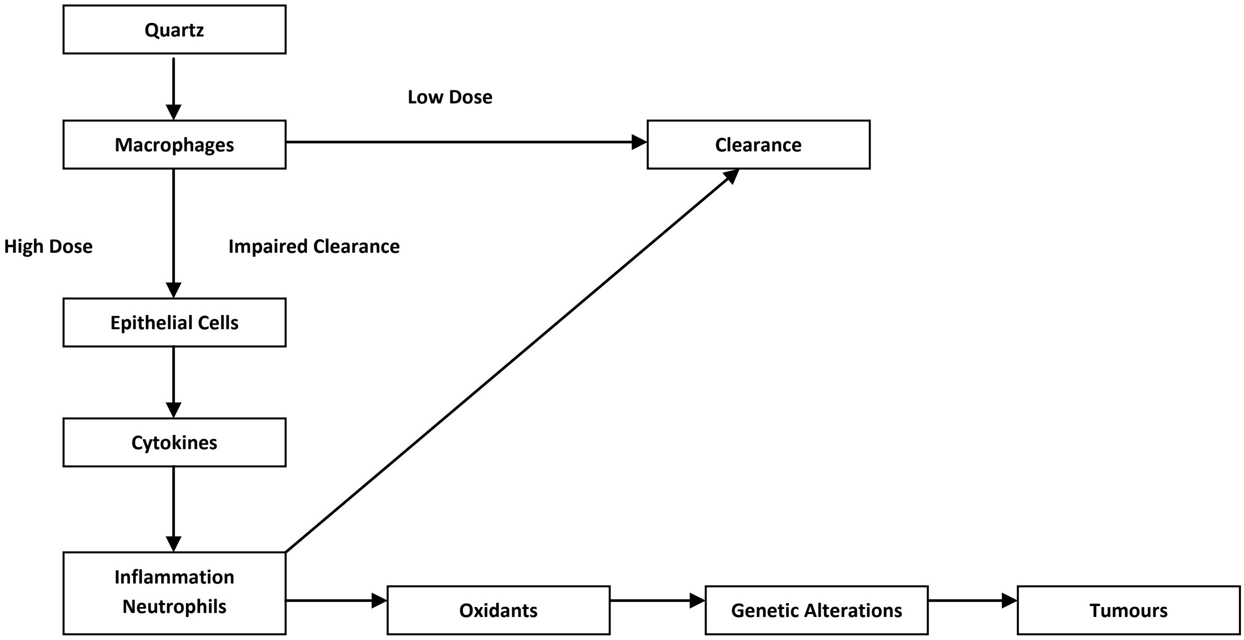

Figure 3: Hypothetical mechanism for carcinogenicity of Quartz (Rice, 2000)

2.5 Nanoparticles

There's another category of particles smaller than 0.1 µm which has been neglected in the past because of the inability to study them and they are known as nanoparticles. Nanoparticles in the atmosphere represent a category of particles with an aerodynamic diameter less than 100 nm (Biswas and Wu, 2005; Lin *et al*., 2006). With a reduction of their size, nanoparticles reveal unique properties. There will also be an increase in the surface free energy which means that the chemical reactivity also increases rapidly due to the size reduction (Ostiguy *et al*., 2008).

The size reduction of particles results in a substantial increase in the specific surface and the surface Gibbs free energy. This physical parameter of free energy reflects the fact that chemical reactivity increases rapidly as particle size diminishes. For example, water has a specific surface of $12.57x10^{-3}$ m^2/g at a diameter of one millimetre but the surface expands to $12.57x10^{+3}$ m^2/g at a diameter of one nanometre. Surface energy also rises by a factor of one million as size decreases from millimetres to nanometres (Zhao and Nalwa, 2007). This means that a nanoparticle has a very large surface, a large proportion of its molecules on that surface and a very high reactivity because the free energy is linked to the reactivity. This increased nanoparticle specific reactivity indicates that the biological behaviour of nanoparticles and their effects on living organisms can change dramatically when particle size decreases. It is clear that the nano-scale, factors such as specific surfaces, surface modifications, number of particles, surface properties (stereochemistry, degree of ionization, oxido-reduction potential, solubility, intermolecular force, interatomic distance between the different functional groups, partition coefficient), concentration, dimensions, structure are all factors that must be considered in toxicity assessment (Ostiguy *et al*., 2008).

Contrary to toxicity studies with larger particles, the initial exposure dose of nanoparticles can involve a degree of uncertainty because these particles can agglomerate into larger particles during the emission process, the exposure process outside the organism or during translocation processes within the organism. This is particularly true during inhalation exposure experiments. This means that the form and physicochemical properties of nanopaticles can evolve and the biological microenvironment can be extremely sensitive to these changes. This results in the possibility of substantial modification of the interactions between the biological systems and the nanoparticles (Zhao and Nalwa, 2007).

Other nanoparticle absorption mechanisms

For nanoparticles, it was recently recognized that two other mechanisms contribute to the absorption of these particles. Sub-micron particles and nanoparticles can pass through the extrapulmonary organs via the bloodstream (Nemmar *et al*., 2002; Oberdörster, 2002; Meiring *et al*., 2005). Once they reach the bloodstream, the nanoparticles can circulate throughout the body and be distributed to the different organs. Moreover, some particles can be transported along the sensory axons to the central nervous system (Oberdörster, 2004; Qingnuan *et al.*, 2002). These two mechanisms could play a major role in the development of certain cardiac or central nervous system diseases, but these mechanisms still have to be proven more clearly in humans (Oberdörster *et al.*, 2005). Katz *et al*., (1984) described neuronal transport from the nose to the brain for 0.02 µm to 0.2 µm microspheres. Several studies showed that when rats are exposed to dusts or welding fumes containing manganese, an insoluble manganese fraction could pass through the hematoencephalic barrier, circulating directly from the nose to the brain via the olfactory nerves. This will allow manganese to accumulate in the brain. Such studies were also performed on various soluble metals and led to the same conclusions (Tjalve and Henriksson, 1999; Brenneman *et al*., 2000; Dorman *et al*., 2002). In humans, studies have clearly shown that manganism is related to manganese accumulation in the brain, although the exact mechanism of this accumulation is still not fully understood (Ostiguy *et al.,* 2008).

Many studies have reported that nanoparticles are closely associated with cardiovascular and respiratory diseases due to their nanosize and complex chemical composition (Oberdörster *et al.,* 2007). Other studies also indicated that there are clear evidence that nanoparticles induce oxidative stress and mitochondrial damage (Li *et al.,* 2003). The toxic effects of nanoparticles that are soluble in biological fluids are related to their chemical components. There is limited data on the toxicity of insoluble nanoparticles, but because of their small size they can easily penetrate into living cells without being soluble (Ostiguy *et al.,* 2008).

2.6 Sampling

Aerodynamic diameter refers to the diameter of a sphere of unit density, which behaves aerodynamically like the particle of the test substance. It is used to compare the aerodynamic behaviour of particles of different sizes, shapes and densities, and play an important in lung deposition of a particle (MHDS 14/3, 2000; EUR, 2002).

2.6.1 Inhalable, thoracic and respirable particles

Inhalable fraction (particles with a size of up to 100 µm, with a 50 % cut-point of 100 µm, i.e., the particulate diameter which is captured with 50 % efficiency): the fraction of airborne material that can be inhaled by the nose or mouth, and is available for deposition in the respiratory tract. The dust that deposits in these areas can accumulate in the sputum or mucus, and can be coughed out or swallowed, making it possible for absorption in the digestive system (Belle and Stanton, 2007). The inhalable occupational exposure limit (OEL) for particles not otherwise classified (PNOC) is 10 mg/m^3.

Thoracic fraction (particles smaller than 30 µm, with a 50 % cut-point of 10 µm) is the fraction of airborne material particles that passes the larynx and may be deposited in the lung airways or the gas exchange regions of the lungs namely the alveoli. There are currently no thoracic OEL listed by the department of minerals and energy (Belle and Stanton, 2007).

Respirable fraction (particles up to 10 µm, with a 50 % cut-point of 4 µm) is the fraction of particles that penetrate the gas exchange region of the lung. Various forms of crystalline silica (such as quartz, cristobalite and tridymite) and coal dust are samples of this fraction (Belle and Stanton, 2007). The OEL for respirable PNOC dust is 3 mg/m^3.

2.6.2 Sampling Equipment

The IOM sampler

The IOM sampler can be used to determine inhalable and respirable exposure in a single sample and meets the international standards of:

- ACGIH sampling criteria for inhalable particulate
- ISO/CEN health-related fraction of bio aerosols
- Preferred sampler for HSE Method MDHS 14/3
- Australian standard for inhalable particulate

(SKC Inc, 2012).

When comparing the sampling efficiency with other commercially available inhalable personal samplers under the same test conditions, the IOM sampler's performance emerged as the best reference instrument for collecting inhalable airborne particles (Zhou and Cheng, 2010). Linnainmaa *et al*. (2008) confirmed the IOM sampler's usability in calm working environments. Because both the cassette and filter are weighed after sampling, underestimation of dust concentrations due to particle deposition on the internal walls does not occur (Linnainmaa *et al*., 2008).

Linnainmaa *et al*. (2008) as well as Zhou and Cheng, (2010) also found that there are certain limitations to the IOM sampler. In general, the sampling efficiency decreases as the wind speed increases. The IOM sampler could possibly collect insufficient material for chemical analysis when it operates at the designed flow rate, of 2 L/min, with a low concentration of aerosol. The sampler's inlet orientation to wind also has an effect on the sampling efficiency. Sampling efficiency is higher, especially for large particles, when the inlet faced directly into the wind (Zhou and Cheng, 2010). This is why there was not made use of the IOM sampler with foam insert for the respirable particles, but a Cyclone sampler.

The Cyclone sampler

The GS-3 Respirable dust cyclone can be used to determine respirable exposures and meets the international standards of:

- ACGIH/ ISO/CEN respirable convention

The GS-3 cyclone is unique and offers some advantages over the aluminium cyclones. With low mean bias and higher flow rate requirements, the GS-3 Cyclone provides better sampling accuracy when compared to the performance of other cyclones used for respirable dust collection. Furthermore, the multiple-inlet GS-3 Cyclone overcomes sampling problems that have been reported with the single-inlet Dorr-Oliver Cyclone (Gautam and Sreenath, 1997).

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CHAPTER 3

ARTICLE

This article may be submitted to *Annals of Occupational Hygiene* for possible publication. The author’s instructions are as follows:

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Characterisation of airborne dust in South African underground and opencast coal mines. A pilot study.

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Word Count: 9634

Abstract:

Dust is a well-known occupational hygiene challenge and has been throughout the years, especially in the coal mining industry. The hazards arising from coal dust will differ between geographical areas due to the unique characteristics of dust from the coal mining environment. It is therefore of upmost importance to identify these qualities or characteristics of coal dust in order to understand the potential hazards it may pose. It is also important to consider the presence of nanoparticles which until recently remained neglected due to the absence of methods to study them.

Aim: The aim of this study was to collect enough airborne dust through static sampling to characterise the physical, morphological as well as elemental properties of inhalable and respirable dust produced at two South African underground and two opencast coal mines. Personal exposure quantification was therefore not of importance in this study. **Method:** Static dust sampling was done at two mining areas of the two opencast and underground coal mines using four Institute of Occupational Medicine (IOM) and four cyclone samplers per area at each mine. A condensation particle counter (CPC) was also used at the opencast areas. The opencast areas included blast hole drilling, drag line and power shovel operations. The underground areas included the continuous miner and roof bolter operations. Gravimetric analyses of the cyclone and IOM samples were done as well as scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis. **Results:** Mine A (opencast and underground) produces higher grade coal than mine B (opencast and underground). Gravimetric analysis indicated higher average inhalable (55.35 mg/m^3) and respirable (2.13 mg/m^3) concentrations of dust in the underground areas when compared to the opencast areas (34.73 mg/m^3 and 0.33 mg/m^3). Blast hole drilling operations indicated higher average inhalable and respirable dust concentrations (39.02 mg/m^3 and 0.41 mg/m^3) when compared to the drag line and power shovel operations (30.44 mg/m^3 and 0.246 mg/m^3). CPC results showed higher average concentrations of sub-micron particles at the blast hole drilling areas per cubic metre (63132 x 10^6) compared to the drag line and power shovel operations (38877 x 10^6). EDS analysis from the opencast areas indicated much higher concentrations of impurities (with lower concentrations of carbon – 33.33%) when compared to samples taken from the underground mining activities (65.41%). The EDS results from the opencast areas differed substantially. The highest concentrations of silica were found at the blast hole drilling areas. EDS results from the underground areas indicated that mine A has slightly higher concentrations of carbon (66.2%) with less impurities when compared to mine B (64.62%). The continuous miner operations showed a higher concentration of impurities when compared to the dust from the roof bolter. SEM results from the opencast areas revealed that the majority of particles are irregularly shaped and the presence of quartz and agglomerations are evident. SEM results from the underground areas were similar except that the roof bolter produced smaller sized particles when compared to the continuous miner. It also seemed that the areas with higher levels of impurities produced more sub-micron particles. **Conclusions:** It is possible to identify the majority of physical and elemental characteristics of coal dust by means of gravimetric analysis, particle counting, SEM and EDS. There were differences found, regarding the morphological; chemical and physical characteristics, between the different opencast and underground areas at mine A and mine B due to the type of mining activity and amount of overburden present. Silicosis, Pneumoconiosis and Chronic obstructive pulmonary disease are some of the possible health concerns. It has been seen that dust from higher grade coal mines contributed to more developed stages of these diseases.

Keywords:

Opencast and underground coal mining, characterisation of dust, dangers of coal dust, nanoparticles, sub-micron particles, silica.

3.1 Introduction

Coal is one of the world's leading sources for the production of energy and will most likely also be the dominant energy source in developing countries for at least the first half of the 21^{st} century (Finkelman *et al*., 2002). The two main methods for mining coal are opencast and underground mining. The most economical method for coal mining or coal extraction from coal seams largely depends on the quality and depth of the coal seam as well as geological and environmental factors such as the density of the overburden (Scott, *et al.*, 2010).

It is well known that dust has been one of the largest occupational hazards through the years (Petavratzi *et al*., 2005) and the coal mining industry is plagued with potential hazards arising from the dust produced at its different operations. Dust is the term used to describe fine particles that are suspended in the atmosphere and that normally have diameters smaller than 100 µm. The behaviour of dust is quite complex as it consists of different phenomena acting on different sized dust particles. For a particle to become airborne it must have an aerodynamic drag force larger than the sum of the particle weight and the interparticle forces (Liu, 2003). Smaller particles on the other hand will behave as a gas and will be influenced by molecular forces. Gravitational and inertial forces will play a bigger role in the behaviour of larger particles when compared to smaller particles. (SIMRAC, 2003). Agglomeration is the result of particles colliding with each other due to their motion and then adheres to form larger particles. It is considered that agglomeration is the most important interparticle phenomenon for airborne particles (Heidenreich *et al.,* 2003).

There are many physical and chemical factors to consider when it comes to the identification and characterisation of dust particles. These factors will include particles size, distribution, surface area as well as elemental composition. Dust particles are mostly composed of different materials or minerals and these particles often form agglomerations with various compositions (Buzea *et al*., 2007). It has been found that coal dust mainly consists of the following minerals: calcite ($CaCO_3$) and dolomite [$(CaMg)(CO_3)_2$] that are carbonate minerals; quartz (SiO_2) and kaolinite [$Al_2Si_2O_5(OH)_4$] wich are a silicate minerals; and illite that is a micaceous and other carbonaceous minerals (Rainey *et al*. 1994). The purity of coal dust is determined by the amount of carbon compared to the amount of other elements or minerals found in the coal dust (Speight, 2005).

Coal dust poses many possible hazards in the coal mining environment. One of the biggest hazards is the possibility of an underground coal dust explosion. For a coal dust explosion to occur the minimum suspended dust concentration must be higher than 50 g/m^3. This is termed the minimum explosive concentration (Cain, 2003). The size of the dust particles also play an enormous role as it has been found that the smaller the suspended particles, the larger the risk of an explosion (Cain, 2003). To prevent coal dust explosion the practice of stone dusting has been implemented. The stone dust, which are mostly composed of calcium and other incombustible substances, will dilute the coal dust and prevent explosions.

There are also many adverse health effects contributed to coal dust in the coal mining environment. Some of these include pneumoconiosis such as Silicosis – a fibrotic disease caused by damaging amounts of respirable free crystalline silica or silicon dioxide (Peters, 1986) and leads to the formation of small, discrete macules or nodules not larger than approximately 10 mm in diameter in the lung tissue (Parkes, 1994), chronic obstructive pulmonary disease (COPD) - a disease state characterised by airflow limitation that is not fully reversible (Boschetto *et al.,* 2006). The nature of these pulmonary diseases depends largely on the area of deposition of airborne particles. Oberdörster (2001) described that different sized particles will be deposited in different pulmonary regions. He indicated that the majority of airborne particles between 5 µm and 100 µm in diameter as well as particles smaller than 0.005 µm in diameter will be deposited in the nasal, pharynx and larynx pulmonary regions. He also found that the majority of particles that will be deposited in the alveolar region are between 0.05 µm and 0.005 µm in diameter.

There's another category of particles which has been neglected in the past because of the inability to study them and they are called nanoparticles. Nanoparticles in the atmosphere represent a category of particles with an aerodynamic diameter less than 0.1 µm (Biswas and Wu, 2005; Lin *et al*., 2006). With a reduction of their size, nanoparticles reveal unique properties (Ostiguy *et al*., 2008). A size reduction results in a substantial increase in the specific surface and the surface Gibbs free energy. This physical parameter of free energy reflects the fact that chemical reactivity increases rapidly as particle size diminishes (Zhao and Nalwa, 2007). Certain studies have reported that nanoparticles are closely associated with cardiovascular and respiratory diseases due to their nanosize and complex chemical composition (Handy and Shaw, 2007; Oberdörster, 2007).

Dust sampling in the mining environment has become a crucial part in monitoring the health risks that the employees are exposed to. Normally favour is given only to gravimetrical analysis of these dust samples to monitor if they exceed the occupational exposure limits (OEL's). There is very little data and literature available on the characteristics (physical and chemical) of dust and especially coal dust. To gain sufficient knowledge of the possible risks the coal dust may hold it is of upmost importance to identify all of the factors by characterizing the coal dust and compare the characteristics of different mining activities.

The aim of this pilot study is to characterise and compare the morphological, physical as well as chemical aspects of dust produced at two South African coal mines. Both of these mines consist of opencast and underground mining activities and will be referred to as mine A and mine B.

3.2 Methodology

The purpose of the methodologies used was to collect sufficient airborne dust in order to:

1. Characterise specific portions based on particle size (aerodynamic diameter) of the airborne dust emitted from various sources during the mining process. The size portions of dust studied were very fine dust (<0.1 µm), respiratory dust (50% cut-off point at 4µm), and inhalable dust (50% cut-off point at 100 µm).
2. Quantitatively studied the sample viewed under the electron microscope for elemental composition (% weight contribution).

3.2.1 Work place description

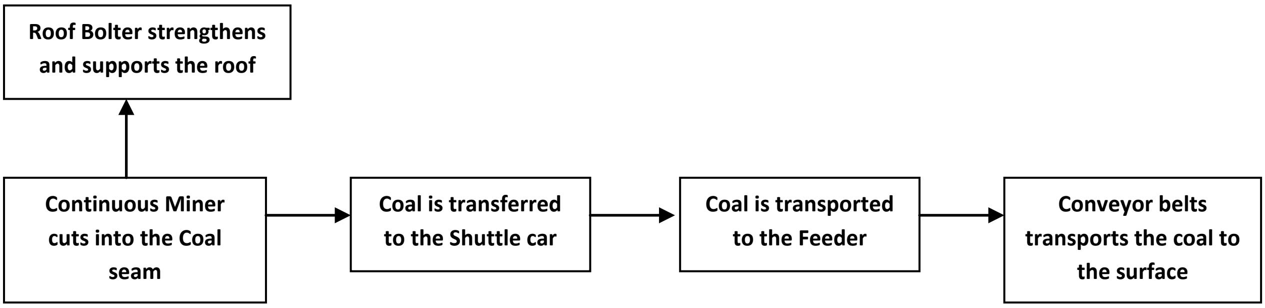

Figure 1: Basic description of the underground coal mining process.

Most coal seams are too deep for opencast mining and require underground extraction. Underground mining currently accounts for 60% of the world’s coal production. In underground mining there are two main methods of mining namely room and pillar and long wall mining. In room-and-pillar mining, coal deposits are mined by cutting a network of ‘rooms’ into the coal seam with a Continuous Miner machine (see figure 1), leaving behind ‘pillars’ of coal to support the roof of the mine (Energy Information Administration, 1994).

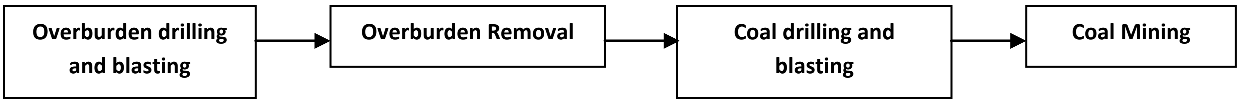

Figure 2: Basic description of the opencast coal mining process.

The first step in opencast mining will be the removal of topsoil and the flora of the mining area by means of blasting and bulldozing as shown in figure 2. The rock and soil covering the coal seam are known as overburden. The second step will be to get rid of this overburden by means of drilling and blasting to loosen this layer. The overburden is then removed by draglines or power shovels and transported to the overburden dumping sites. Once the coal seam is exposed, it will be drilled, fractured by means of explosives and then systematically mined in strips. The coal will then be loaded for transport to either the coal preparation plant or direct to where it will be used (Ghose and Majee, 2000).

3.2.2 Gravimetric sampling of respiratory and inhalable dust

The purpose of this sampling was to gather enough respirable and inhalable dust for electron microscopy analysis. For the sampling of inhalable dust four IOM samplers were used per area. Static sampling was conducted according to the NIOSH 5700 method. MCE filters were used for their capability to capture sub-micron particles (Furuuchi *et al.,* 2010). Samples were transported in a shock resistant carry case. For the sampling of respirable dust GS-3 cyclones were used. There were also four samples taken per area. Static sampling was conducted at a 2.5 L/min flow rate (according to the NIOSH 0600 method). The reason for sampling respiratory and inhalable portions is to evaluate possible differences found in morphological (form and shape of the particles), physical (particle size distribution) and elemental composition of the different size groups. This could help to better identify the potential hazards the dust may have.

3.2.3 Sub-micron particle counting

The sub-micrometre particles were counted with a condensation particle counter (CPC) Model 3007 from TSI®. It is a handheld, direct reading device capable of measuring the particle number concentration per cubic centimetre of particles between 10 nm and 1 µm. The counting was done during the same time that the inhalable and respirable samples were taken. The CPC particle counter could not be used underground as the instrument was not classified as inherently safe, which was a prerequisite given by the mine management for any instrument used underground. It was only used during the opencast mining operations. The importance for including the measurement of particles in the sub micrometre range is illustrated by Figure 3 that clearly shows that a large percentage of the sub micrometre particles can be deposited in the alveolar region.

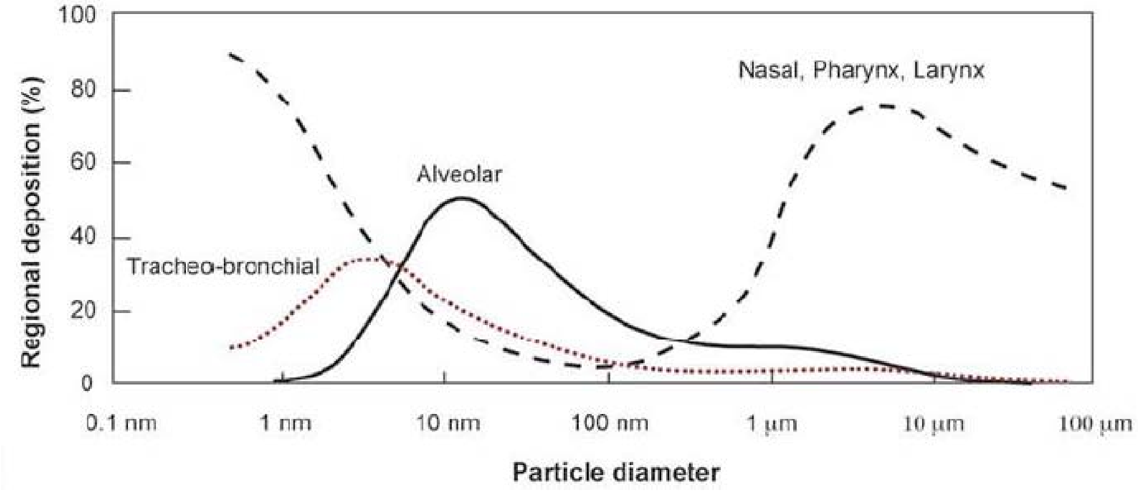

Figure 3: Graphic illustration of where different sized particles are deposited in the pulmonary regions (Oberdörster, 2001).

Figure 3 has been adopted from Oberdörster (2001). This graph illustrates the pulmonary regions where different sized dust particles are deposited. From this image it is clear that the majority of particles between 100 µm and 1 µm as well as those between 0.005 µm and 0.001 µm (5 nm to 1 nm) will be deposited in the nasal, pharynx and larynx regions. The particles that mostly reach the alveolar regions are sized between 0.05 µm and 0.005 µm but starts increasing from 0.5 µm. Using this Figure it is possible to determine where different sized coal dust particles may be deposited in the pulmonary region.

3.2.4 Electron microscopy and EDS analysis

The dust on the filters were mounted on scanning electron microscopy (SEM) stubs with double sided copper tape and studied with a Philips XL30 electron microscope which made it possible to identify dimensionality, morphology, uniformity and state of agglomeration. Sizes down to 0.05 µm could be studied. To view nanoparticles some of the stub samples were spatter coated with gold/palladium (Newbury *et al.,* 1986).

An elemental analysis was also done on the stub samples by energy dispersive X-ray spectroscopy (EDS). EDS is a very powerful method for gathering information on elemental composition of samples as little as a cubic micrometre of material (Reddy *et al.,* 2000). The EDS was attached to the SEM and all the information on the elemental composition was made on the same samples viewed under the SEM.

3.2.5 Mining areas monitored

Two mines each with opencast and underground sites (mines) were included in this study. Two areas in each mine were identified as areas with high dust emissions according to historical data. The areas were identified by the local occupational hygienist during a walkthrough survey. The areas identified at opencast mine A included the blast hole drilling and drag line operations. At opencast mine B it included the blast hole drilling and power shovel operations. The areas identified at the underground mine A and B included the continuous miner and roof bolter areas. Four IOM and four cyclone samples were taken at each area to enhance the possibility that one of the samples would have enough dust on the filter for SEM and EDS analysis.

Blast hole drilling operations:
A self-propelled crawler-mounted electric blast hole drilling rig is designed for drilling vertical and inclined holes at opencast mining. The drilling rig provides drilling of holes with 160-215 mm in diameter and 40 m in depth. Explosive charges were then placed in these holes and detonated to loosen the overburden and fracture the coal seams. Dust samples and CPC measurements were taken 5 metres from the drilling rigs (Scott *et al.*, 2010).

Drag line operations:
Draglines are used for opencast mining of mineral resources with no handling facilities and also during construction of the canals, irrigation and various water-development projects. Draglines are intended to excavate soils of up to the 4th category of hardness inclusive. In this case the soils of the 3rd and 4th category are to be preliminarily loosened by blasting. Dust samples and CPC measurements were taken 20 metres from the drag lines for safety reasons.

Power shovel operations:

Power shovels are the main stripping and mining machines. These shovels are designed to mine rocks with the volume weight in the pillar being no more than 2800 kg/m^3 and provide damping of the material both on trucks and to the spoil bank. Dust samples and CPC measurements were also taken 20 metres from the power shovels (Ghose and Majee, 2000).

The underground areas at mine A and mine B included the continuous miner and roof bolting operations. Each of these areas was sampled twice with IOM and cyclone samplers at a distance of 10 metres.

Continuous miner operations:

A continuous miner machine has a large rotating steel drum equipped with tungsten carbide teeth that scrape coal from the seam. This machine operates in a “room and pillar” system, where the mine is divided into a series of work areas cut into the coal bed (Hartman, 1992).

Roof bolter operations:

A roof bolter is a hydraulically driven miner-mounted bolting rig used to install rock bolts in mines, tunnels, underground power plants and storage facilities. Roof bolting is also a common application in underground coal mines for securing mine roofs to be self-supportive.

3.2.6 Statistical analysis

Because this pilot study only focused mainly on the on the morphological, physical and elemental aspects of a micro sample of dust on the SEM stubs carried over from the gravimetric sample, it was handled as a descriptive study which limits the possibility for statistical analysis other than descriptive statistics. The averages and 90th percentiles were calculated for the inhalable and respirable dust samples taken at each area. The 90th percentile provides a more accurate result when compared to the average of the four IOM and four cyclone samples taken at each area. The average CPC and EDS results were also calculated. Only average EDS results were presented because some IOM and cyclone samples could not be analysed due to low amounts of collected dust.

3.3 Results

Figure 4 illustrates the average inhalable dust measurements from mine A and mine B (the average, 90th percentile (→) as well as minimum and maximum results of four IOM samples per area at each mine). The opencast areas included the blast hole drilling areas (A-σ = 39.5 mg/m^3; B-σ = 43.77 mg/m^3); the drag line area (A-σ = 26.8 mg/m^3) and the power shovel area (B-σ = 42.1 mg/m^3). The underground areas included the continuous miner areas (A-σ = 64.7 mg/m^3; B-σ = 70.5 mg/m^3) as well as the roof bolter areas (A-σ =53.1; B-σ = 61.2 mg/m^3). The average concentration of inhalable dust at the specific areas in the underground areas was 39.9% higher than the concentration in the opencast mine areas. The concentrations of the inhalable dust were higher mine B than at the same areas at mine A. The dust concentrations of the inhalable samples were more than enough to easily transfer an adequate sample to the SEM stubs for analysis.

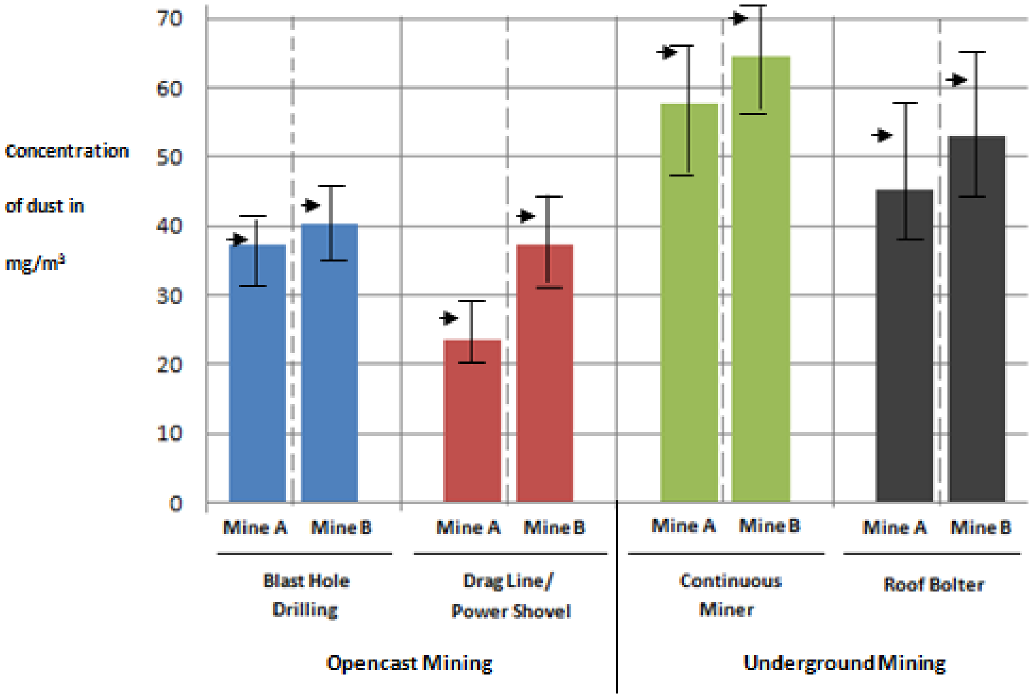

Figure 4: Average, σ = 90th percentile (→), minimum and maximum inhalable dust concentrations from the different mining activities.

Figure 5 illustrates the average respirable dust measurements from mine A and mine B (the average, 90th percentile (→) as well as minimum and maximum results of four cyclone samples per area at each mine). The opencast areas included the blast hole drilling areas (A-σ = 0.62 mg/m^3; B-σ = 0.45 mg/m^3); the drag line area (A-σ = 0.29 mg/m^3) and the power shovel area (B-σ = 0.31 mg/m^3). The underground areas included the continuous miner areas (A-σ = 3.32; B-σ = 3.07 mg/m^3) as well as the roof bolter areas (A-σ =1.42 mg/m^3; B-σ = 1.28 mg/m^3). It is clear that the average respirable dust concentrations at the underground areas are much higher than those from the opencast areas. There is also a clear indication that the mining areas at mine A produced higher concentrations of respirable dust when compared to the same areas at mine B. These respirable concentrations differs from the inhalable concentrations results. The dust concentrations of the respirable samples from the underground areas were more than enough to easily transfer an adequate sample to the SEM stubs for analysis. The respirable dust concentrations from the opencast areas however were not enough for SEM analysis.

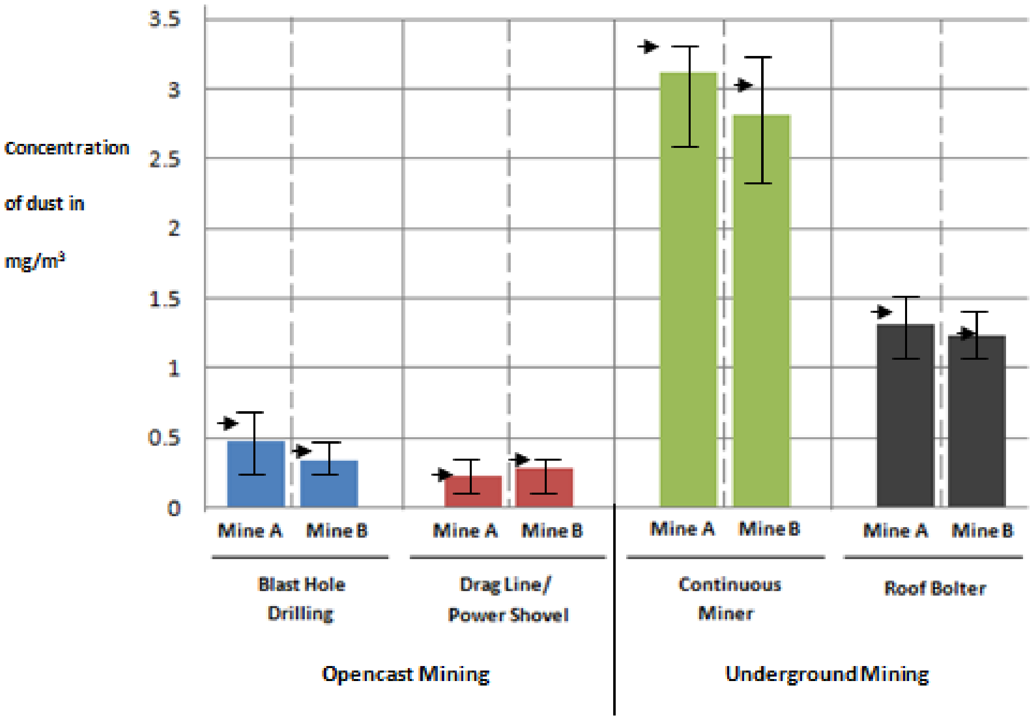

Figure 5: Average, σ90th percentile (→), minimum and maximum respirable dust concentrations from the different mining activities.

Table 1 illustrates the minimum, maximum and average results from the condensation particle counter (CPC) which measures the amount of particles between 0.01 µm and 1 µm in diameter per cubic centimetre. In the table the measurements are converted to cubic metres. Measurements were only taken twice at all the opencast areas. It is clear that the drilling areas produce more sub-micron particles when compared to the drag line and power shovel areas.

Table 1: Average CPC measurements at the opencast areas at both mine A and mine B

Mine	**Area**	**Average CPC reading Particles \ m^3**		
		Minimum	**Maximum**	**Average**
1 Mine A	**Blast hole drilling**	5 472 x 10^6	147 570 x 10^6	69 256 x 10^6
2 Mine A	**Drag line**	11 653 x 10^6	115 679 x 10^6	27 343 x 10^6
3 Mine B	**Blast hole drilling**	17 912 x 10^6	205 541 x 10^6	57 008 x 10^6
4 Mine B	**Power shovel**	12 542 x 10^6	182 744 x 10^6	50 411 x 10^6

Figure 6 illustrates an electron microscopy photo of inhalable dust sampled at the blast hole drill at mine A. This image gives insight to the morphology and possible mineral composition of the dust found in this area. From this image it is clear that the majority dust particles are between 10 and 100 µm and have a large surface area available for other particles to adhere to. There is clear evidence of silica dioxide (quartz) and carbonaceous material. The majority of particles are irregularly shaped. There is also fibre shaped particles.

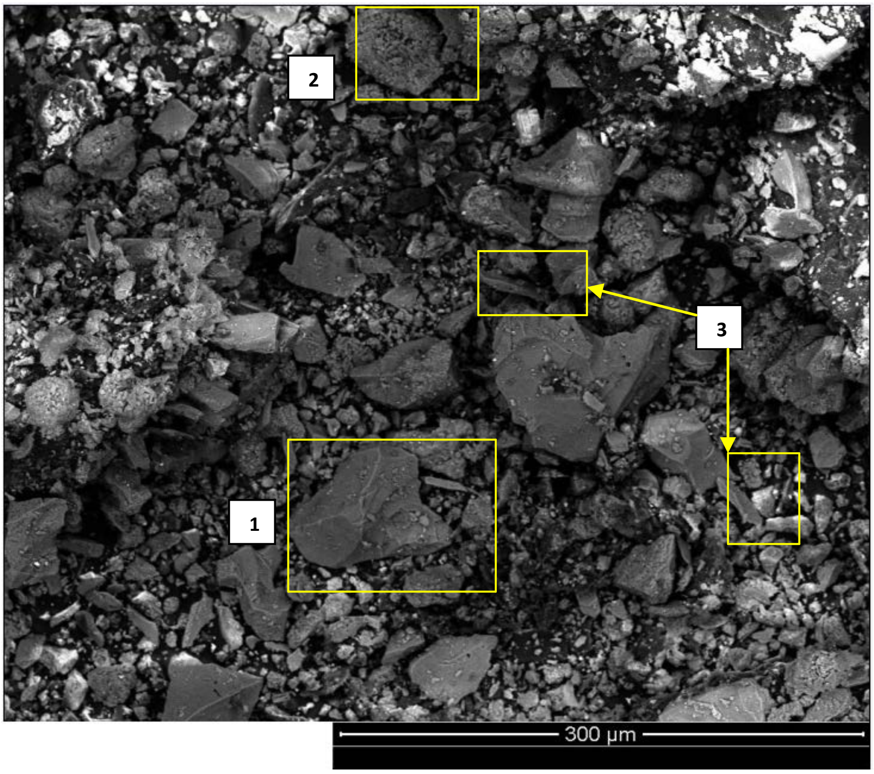

Figure 6: Electron microscopy photo of inhalable dust sample taken from the blast hole drill at mine A (1- quartz; 2- carbonaceous material; 3- fibre shaped particles)

Table 2 illustrates that carbon, oxygen and silica (combined as silica dioxide) are the main contributors to the mass of the inhalable dust from the blast hole drilling area at mine A.

Table 2: Average EDS results of elemental composition of inhalable dust from the blast hole drilling area at mine A

Element	Percentage weight contribution (%)
Carbon	33.57
Oxygen	44.41
Aluminium	3.26
Silica	16.21
Sulphur	0.25
Potassium	0.80
Calcium	0.13
Titanium	0.42
Iron	0.94

Figure 7 illustrates an electron microscopy photo of inhalable dust sampled at the drag line at mine A. From this image it is clear that the visible dust particles are between 10 and 100 µm and have a large, flat surface areas. There is clear evidence of silica dioxide and carbonaceous material indicated in the image. The disk shaped particles and the amount of aluminium and silica (Table 9) could indicate the presence of the mineral kaolinite. There is also fibre like particles present.

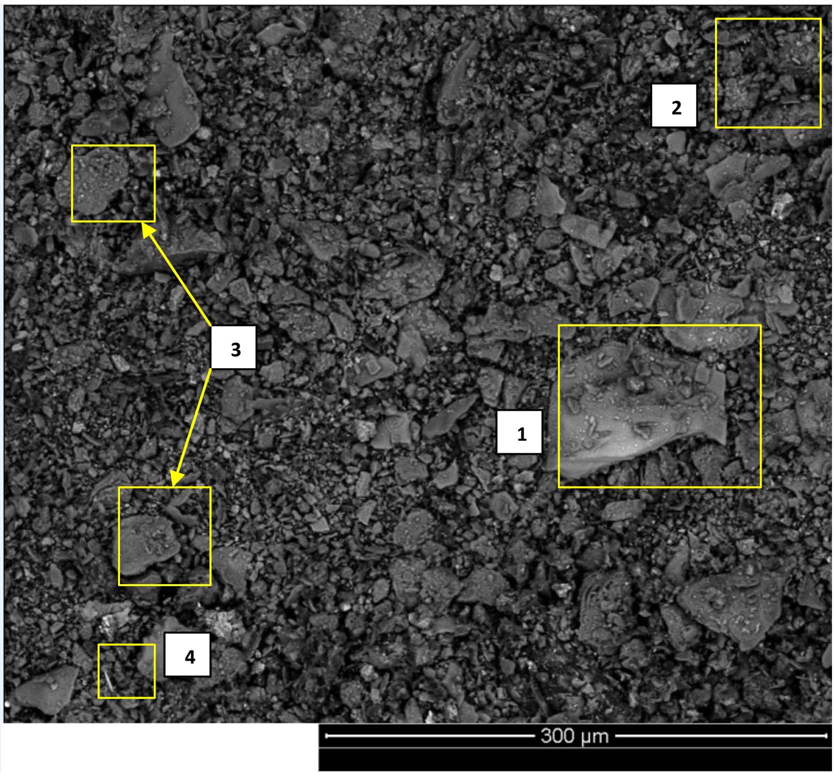

Figure 7: Electron microscopy photo of inhalable dust sample taken from the drag line area at mine A (1- quartz; 2- carbonaceous material; 3- possible kaolinite disks; 4- fibre like particles)

Table 3 illustrates that carbon, oxygen, aluminium and silica are the main contributors to the mass of the inhalable dust from the drag line area at mine A.

Table 3: Average elemental composition of inhalable dust from the drag line area at mine A

Element	Percentage weight contribution (%)
Carbon	26.26
Oxygen	48.06
Magnesium	0.28
Aluminium	8.79
Silica	11.67
Sulphur	0.19
Potassium	1.05
Calcium	0.36
Titanium	0.51
Iron	2.27

Figure 8 illustrates an electron microscopy photo of inhalable dust sampled at the blast hole drilling area at mine B. The majority of visible inhalable particles are between 10 and 90 µm in diameter. There is clear evidence of silica dioxide and carbonaceous material with possible kaolinite and illite minerals. The formation of agglomerates is very dominant in this photo. The larger particles (such as silica) have a more three dimensional shape when compared to the previous SEM photos.

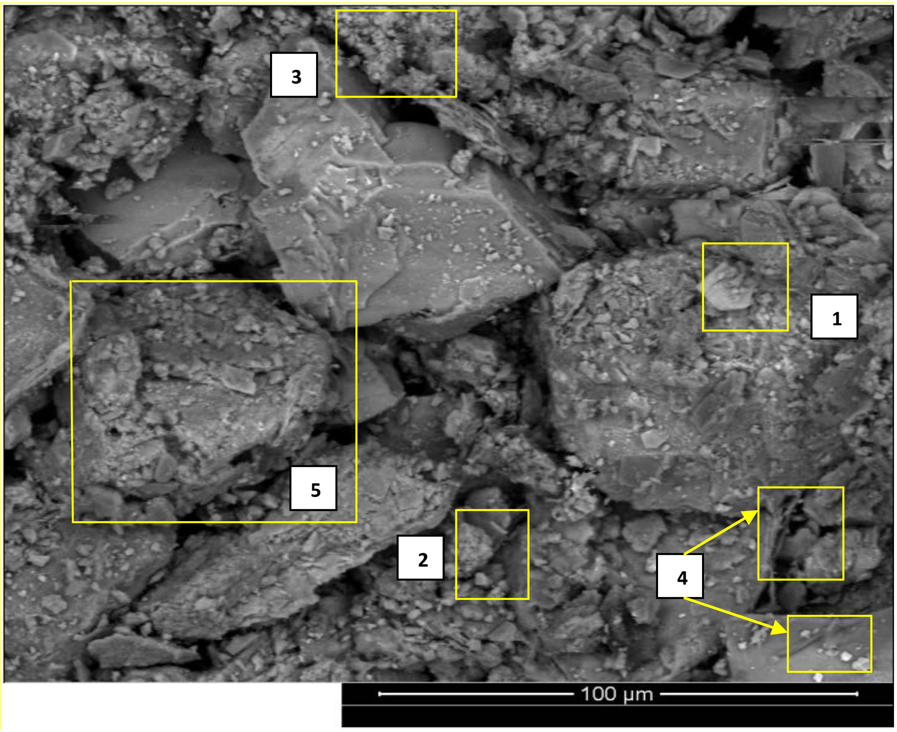

Figure 8: Electron microscopy photo of inhalable dust sample taken from the blast hole drilling area at mine B (1- quartz; 2- carbonaceous material; 3- possible kaolinite and illite; 4- fibre shaped particles; 5- agglomerates).

Table 4 illustrates that oxygen, carbon and especially silica are the main contributors to the mass of the inhalable dust from the blast hole drilling area at mine B.

Table 4: Average elemental composition of inhalable dust from the blast hole drilling area at mine B

Element	Percentage weight contribution (%)
Carbon	11.9
Oxygen	52.36
Sodium	0.57
Magnesium	0.81
Aluminium	6.03
Silica	15.46
Potassium	2.40
Calcium	6.25
Titanium	0.55
Iron	3.67

Figure 9 illustrates an electron microscopy photo of inhalable dust from the power shovel area at mine B. The visible particles are between 20 and 200 µm in diameter and are irregularly shaped with less evidence of agglomeration. From this image and Table 5 it is clear that the dust particles are mostly carbonaceous in nature. There is also clear evidence of silica dioxide.

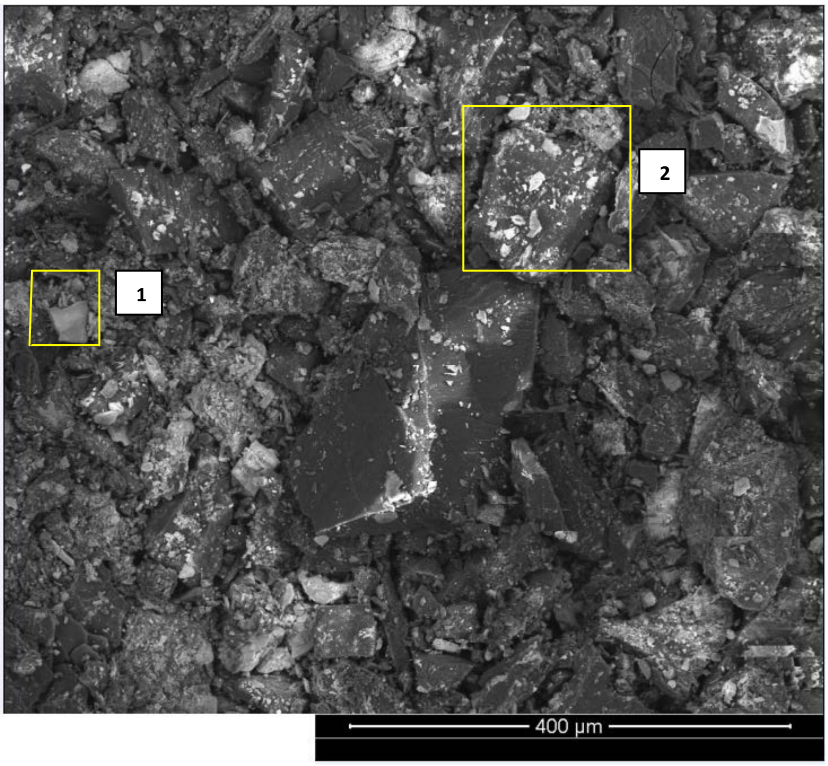

Figure 9: Electron microscopy photo of inhalable dust sample taken from the power shovel area at mine B (1- quartz; 2- carbonaceous material)

Table 5 illustrates that carbon, oxygen and silica are the main contributors to the mass of the inhalable dust from the power shovel area at mine B and that the carbon is much higher when compared to the other opencast areas indicating more carbonaceous material.

Table 5: Average elemental composition of inhalable dust from the power shovel area at mine B

Element	Percentage weight contribution (%)
Carbon	61.58
Oxygen	29.45
Magnesium	0.11
Aluminium	2.27
Silica	4.68
Sulphur	0.44
Potassium	0.26
Calcium	0.61
Titanium	0.23
Iron	0.37

Figure 10 illustrates an electron microscopy photo of inhalable dust from the underground areas at mine A and mine B. The photos from these areas are very similar and thus only one is presented. From this image it is clear that there is a larger amount of smaller sized and fibre like particles when compared to the opencast areas. The formation of agglomerates is also visible. The majority of particles seen are between 5 and 60 µm in diameter and are shaped irregularly.

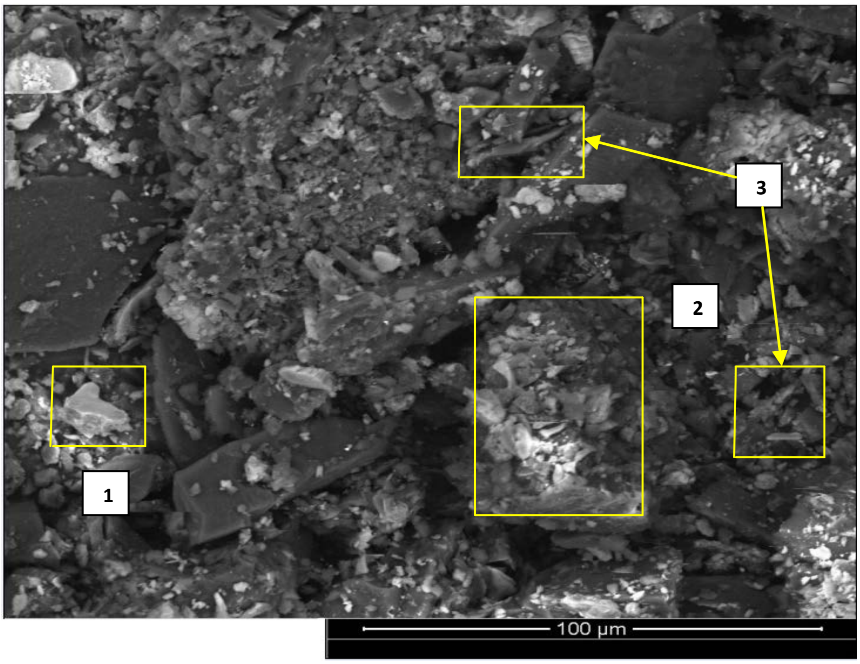

Figure 10: Electron microscopy photo of inhalable dust taken from the underground areas at mine A and mine B (1- quartz; 2- carbonaceous material; 3- fibre shaped particles)

Table 6 illustrates that carbon and oxygen (and to a lesser extent silica) are the main contributors to the mass of the inhalable dust from the underground areas at mine A and mine B. Mine A has less impurities when compared to Mine B.

Table 6: Average elemental composition of inhalable dust from the underground areas of mine A and mine B

Element	Percentage weight contribution (%) from continuous miner at mine A	Percentage weight contribution (%) from continuous miner at mine B	Percentage weight contribution (%) from roof bolter at mine A	Percentage weight contribution (%) from roof bolter at mine B
Carbon	63.58	62.05	64.83	63.03
Oxygen	27.07	29.33	26.40	28.32
Magnesium	0.73	0.24	0.52	0.20
Aluminium	1.62	2.49	1.23	2.16
Silica	1.8	3.41	1.48	2.23
Sulphur	0.47	0.44	0.31	0.33
Potassium	0.00	0.13	0.00	0.08
Calcium	2.71	1.51	2.29	1.94
Iron	0.82	0.23	0.69	0.18

Figure 11 is an electron microscopy photo of respirable dust from the continuous miner areas at mine A and mine B (underground). The photos from these areas are very similar and thus only one is presented. The majority of visible respirable particles are between 0.5 and 10 µm with the exception of a few. These particles are also irregularly shaped. There is clear evidence of carbonaceous material and quartz.

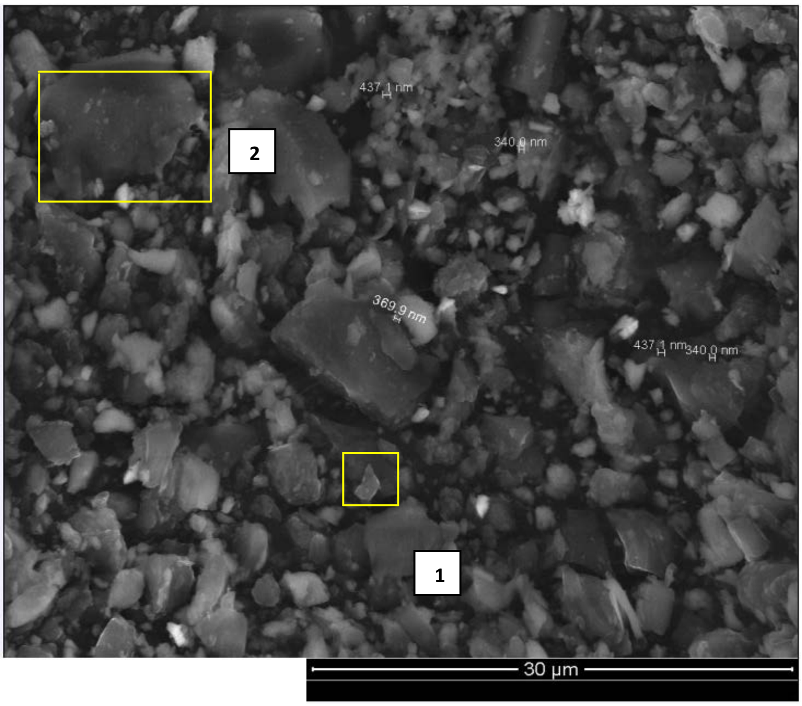

Figure 11: Electron microscopy photo of respirable dust taken from the continuous miner areas at mine A and mine B (1- quartz; 2- carbonaceous material)

Table 7 illustrates that carbon and oxygen are the main contributors to the mass of the respirable dust from the continuous miner areas and that there are slightly more impurities found at Mine B than at Mine A.

Table 7: Average elemental composition of respirable dust from the continuous miner areas of mine A and mine B

Element	**Percentage weight contribution (%) from continuous miner at Mine A**	**Percentage weight contribution (%) from continuous miner at Mine B**
Carbon	67.82	66.41
Oxygen	27.93	29.03
Magnesium	0.26	0.21
Aluminium	0.98	1.11
Silica	1.12	1.59
Sulphur	0.44	0.39
Potassium	0.00	0.07
Calcium	0.94	1.05
Iron	0.49	0.14

Figure 12 illustrates an electron microscopy photo of respirable dust from the roof bolter areas at mine A and mine B (underground). The photos from these areas are very similar and thus only one is presented. All of the particles found in this sample are smaller than 10 µm and ranges between 0.4 and 6 µm in diameter. The majority of particles are carbonaceous but there is also evidence of quartz particles.

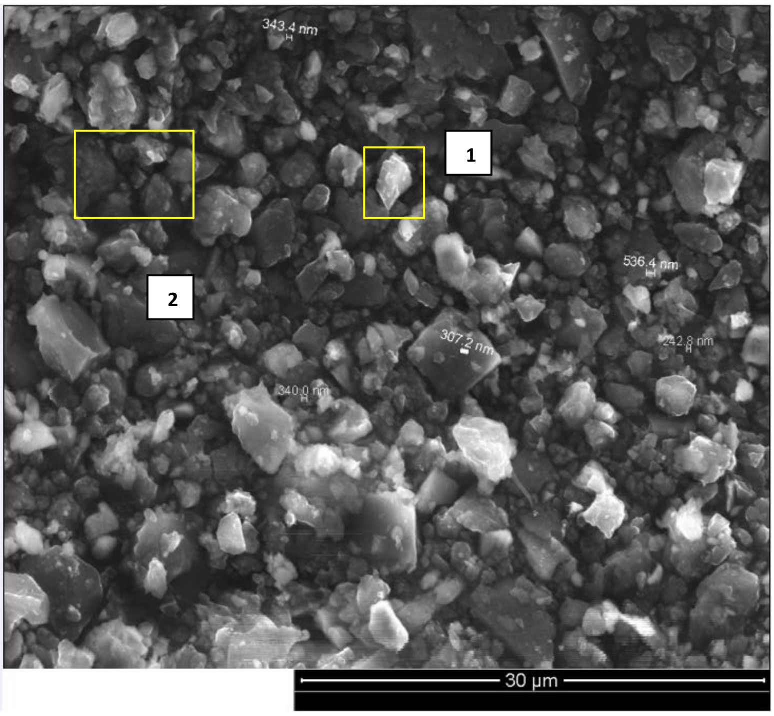

Figure 12: Electron microscopy photo of respirable dust taken from the roof bolter areas at mine A and mine B (1- quartz; 2- carbonaceous material)

Table 8 illustrates that carbon and oxygen are the main contributors to the mass of the respirable dust from the roof bolter areas (underground) at mine A and mine B.

Table 8: Average elemental composition of respirable dust from the roof bolter areas of mine A and mine B

Element	Percentage weight contribution (%) from roof bolter at Mine A	Percentage weight contribution (%) from roof bolter at Mine B
Carbon	68.53	66.98
Oxygen	27.37	28.62
Magnesium	0.36	0.19
Aluminium	0.93	1.03
Silica	1.04	1.24
Sulphur	0.39	0.31
Calcium	0.96	0.99
Iron	0.43	0.12

Figure 13 illustrates the average EDS results for the inhalable dust from the opencast mines. The elements include carbon, oxygen and silica. These elements made up the highest percentage of the dust samples. It is clear that the percentage of these elements differs between the different opencast areas. Mine A shows an overall higher concentration of carbon than mine B except for the power shovel area at mine B with the highest level of carbon found at the two opencast mines. There were also high concentrations of silica found at the blast hole drilling areas as well as the drag line. Less silica was found at the power shovel area.

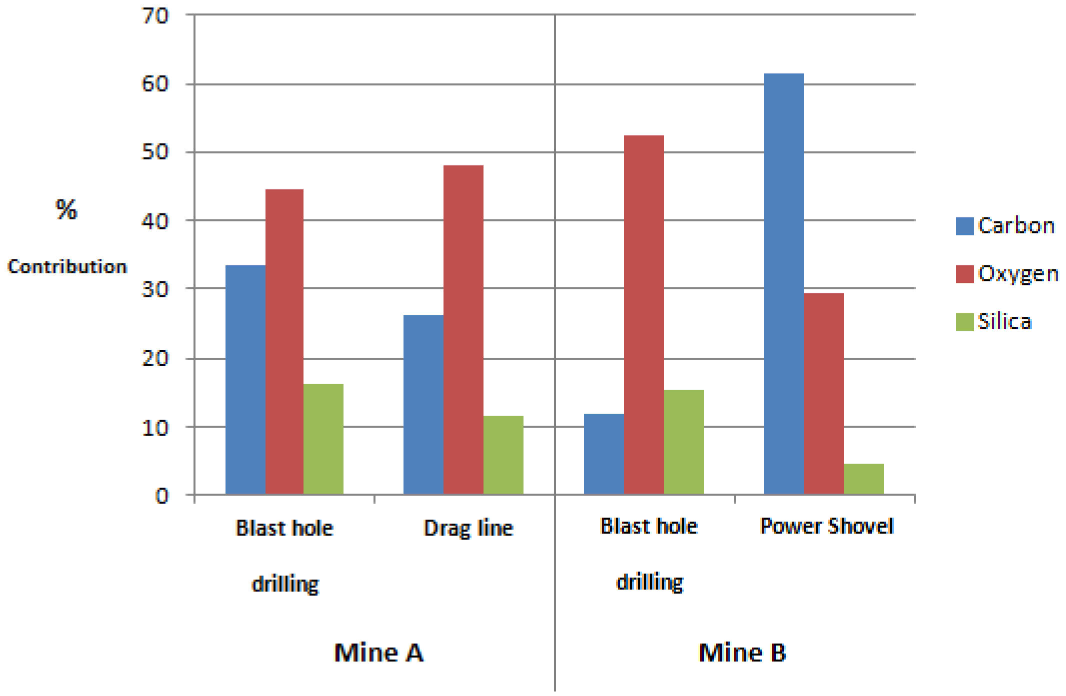

Figure 13: Average elemental composition of inhalable dust taken from all areas at both opencast mines. Carbon, oxygen and silica were the highest contributing elements found in the dust samples.

Figure 14 illustrates the average EDS results for the inhalable dust from the opencast mines. The elements include sulphur, potassium, calcium, titanium, iron, magnesium and aluminium. These elements made up the lower contributing elements found in the opencast inhalable dust samples. It is clear that the composition of the dust from the opencast areas differs from each other. At mine A the majority of lower contributing elements were aluminium and iron and at mine B it was aluminium, calcium and iron.

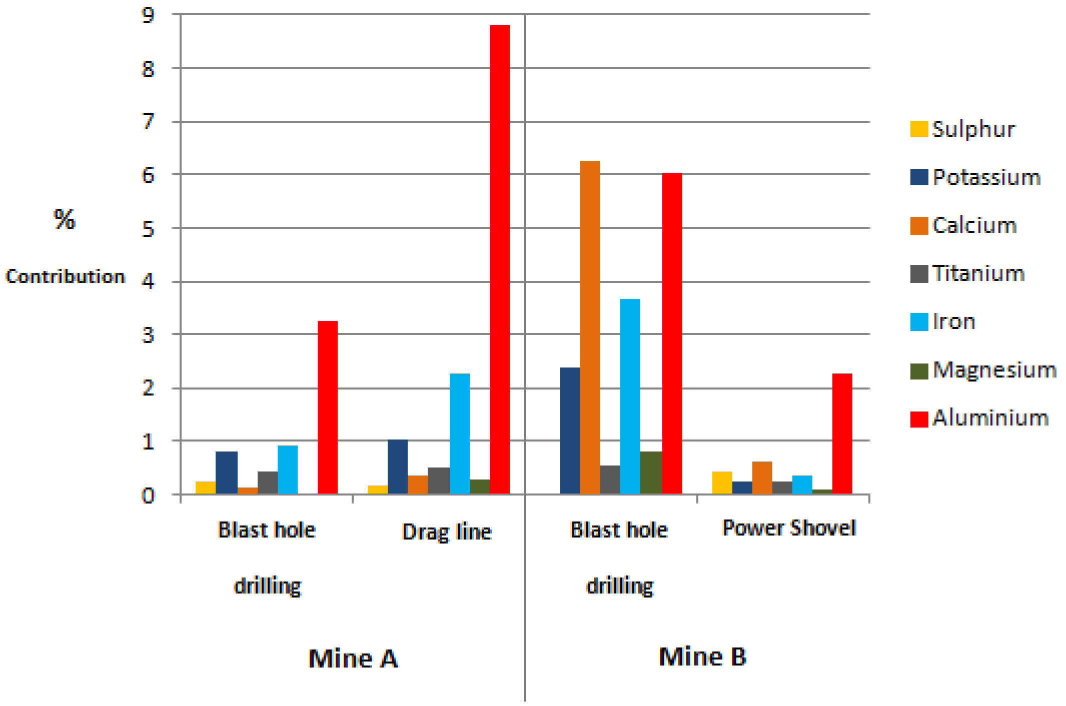

Figure 14: Average elemental composition of the lower contributing elements found in the inhalable dust taken from all areas at both opencast mines.

Figure 15 illustrates the average EDS results for the inhalable dust from the underground mines. The elements include carbon, oxygen and silica. These elements made up the highest contributing percentage of the dust samples. The differences in the composition are not as striking as at the opencast areas. Mine A shows a slightly higher concentration of carbon than mine B. At both mines the dust from the roof bolter had a higher concentration of carbon than the dust from the continuous miner. There were also higher concentrations of silica found at mine B as well as higher concentrations of silica at the continuous miners than at the roof bolters at both underground mines.

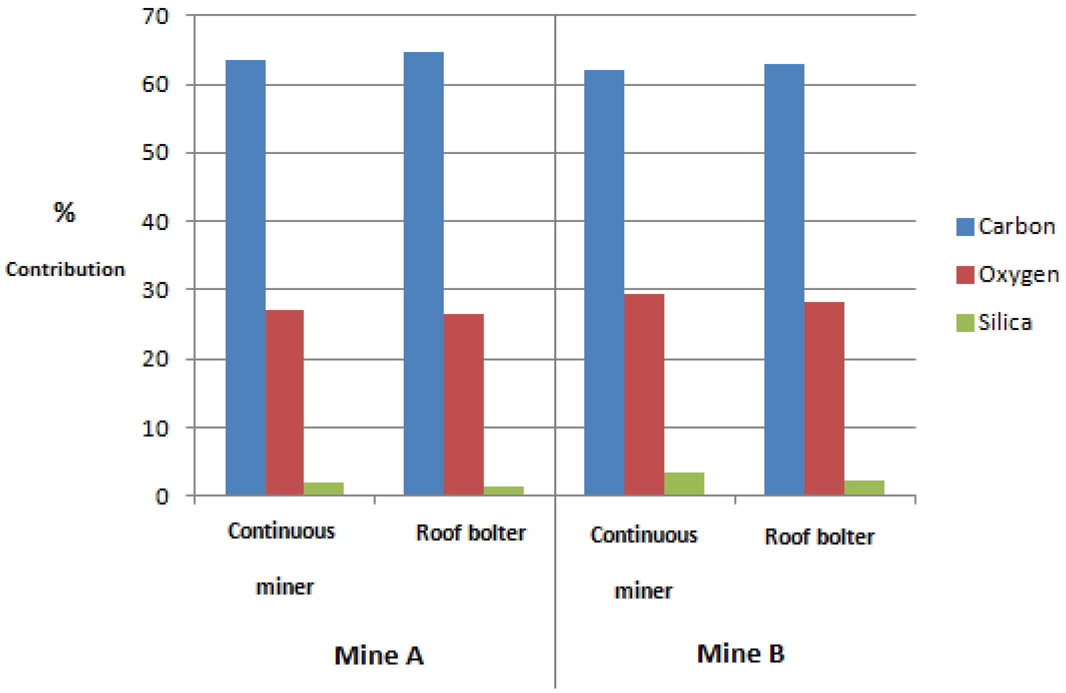

Figure 15: Average elemental composition of inhalable dust taken from all areas at both underground mines. Carbon, oxygen and silica were the highest contributing elements found in the underground inhalable dust samples.

Figure 16 illustrates the average EDS results for the inhalable dust from the underground mines. The elements include sulphur, potassium, calcium, titanium, iron, magnesium and aluminium. These elements made up the lower contributing elements found in the underground inhalable dust samples. It is clear that these elements of the inhalable dust from the underground areas differ from each other. At mine A the majority of lower contributing elements were calcium, aluminium and iron. At mine B it was aluminium, calcium and sulphur.

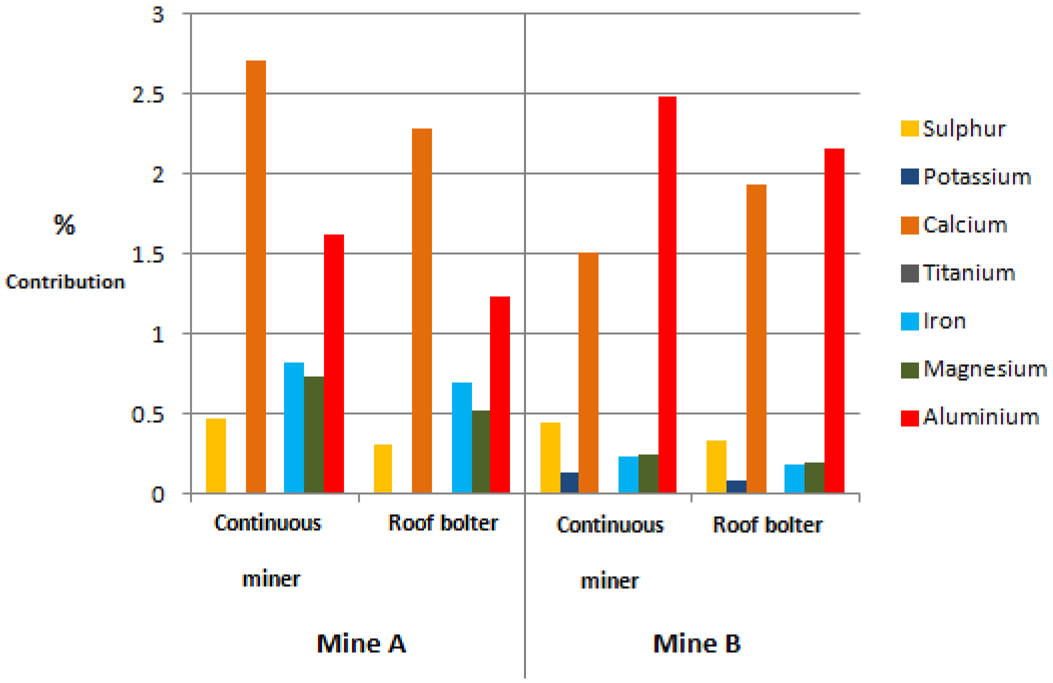

Figure 16: Average elemental composition of the lower contributing elements found in the inhalable dust taken from all areas at both underground mines.

Figure 17 illustrates the average EDS results for the respirable dust from the underground areas at both mines. The elements include carbon, oxygen and silica which contributed the most to the composition of the respirable dust. The respirable dust compositions from the underground areas are very similar except that the roof bolter areas at both mines show larger quantities of carbon when compared to the continuous miner areas. Mine A also shows an overall higher concentration of carbon than mine B. Again it can be seen that the respirable dust from mine B contains more silica than the respirable dust from mine A.

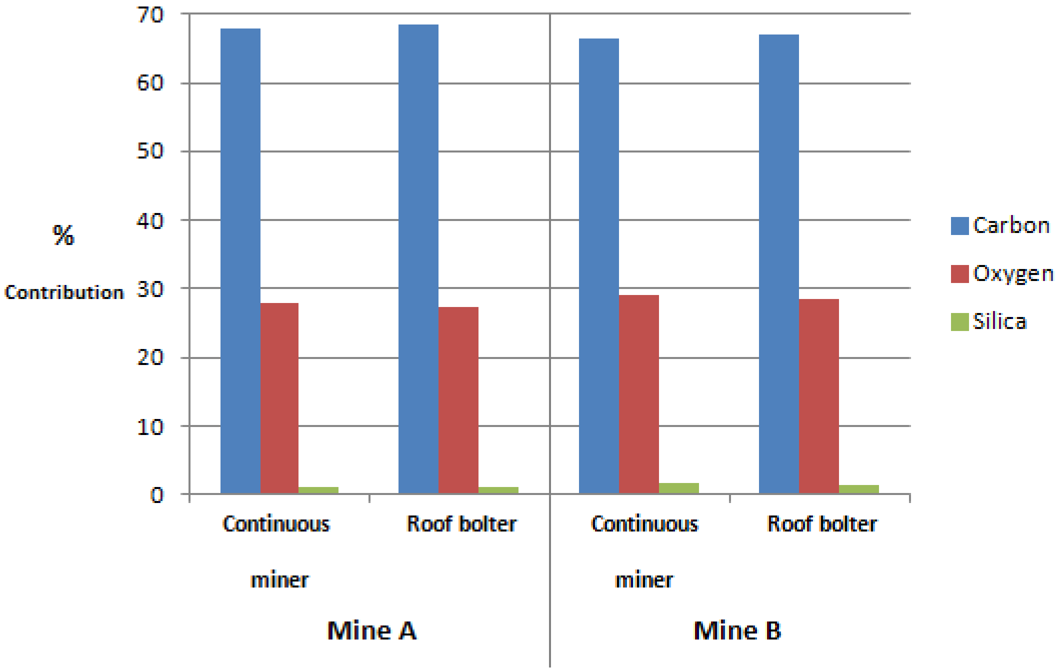

Figure 17: Average elemental composition of the respirable dust taken from all areas at both underground mines. Carbon, oxygen and silica were the highest contributing elements found in the underground respirable dust samples.

Figure 18 illustrates the average EDS results for the lower contributing elements found in the respirable dust from the underground mines. These elements include sulphur, potassium, calcium, titanium, iron, magnesium and aluminium. These elements made up the lower contributing elements found in the underground respirable dust samples. Again these elements of the respirable dust from the underground areas differ from each other. At Mine A the majority of lower contributing elements were calcium, aluminium and iron. At mine B it was aluminium, calcium and sulphur.

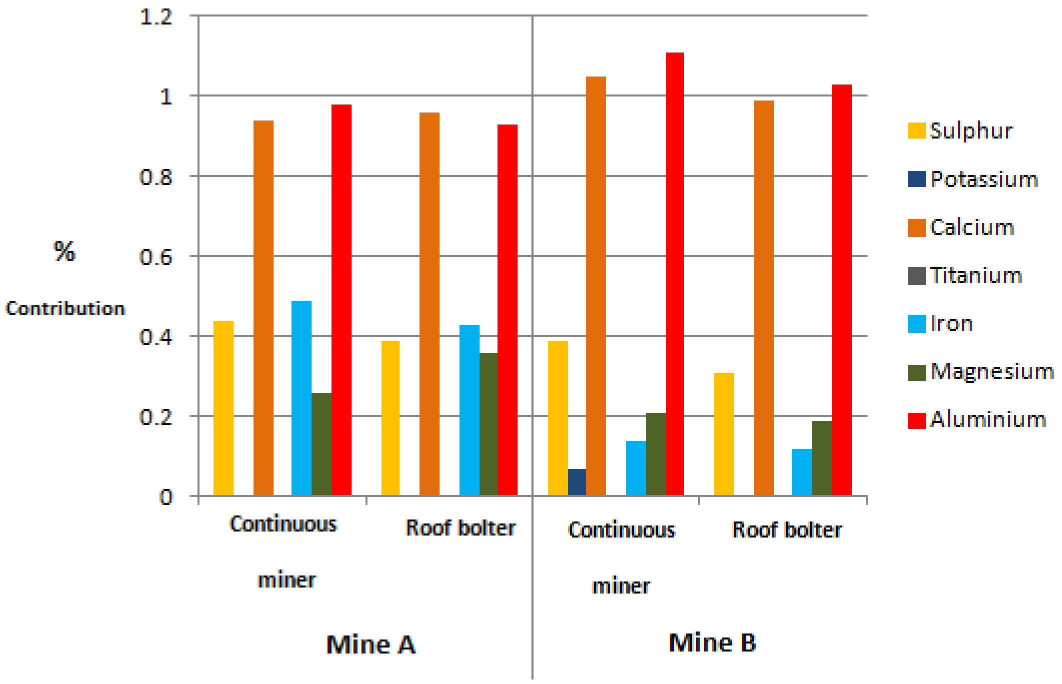

Figure 18: Average elemental composition of the lower contributing elements found in the respirable dust taken from all areas at both underground mines.

Table 9 illustrates the possible minerals contributing to the impurities found in the dust samples. Previous studies have shown that these minerals are mostly found in areas rich in carbon which is associated with coal mining (Rainey *et al*. 1994).

Table 9: Minerals contributing to the impurities found in the dust samples

Impurity	Possible Mineral
Magnesium (Mg)	Dolomite; Illite
Aluminium (Al)	Kaolinite; Illite
Silica (Si)	Quartz; Kaolinite; Illite
Calcium (Ca)	Calcite; Dolomite
Potassium (K)	Illite
Iron (Fe)	Illite

Figure 19 illustrates an electron microscopy photo of the nanoparticles from the blast hole drilling area at mine A. The majority of sub-micron particles seen in this photo are clinging to larger clay like structures. The smallest independent particles found are between 0.02 µm and 0.03 µm in diameter. The majority of these sub-micron particles also have irregular shapes with sharper edges. Many of the smaller particles seem to be independent, but are in fact part of the larger particles. The formation of agglomerates is also clear and the disk shaped particles may indicate the presence of kaolinite. EDS analysis were not done because the sample was spatter coated with gold\palladium to make the nanoparticles visible.

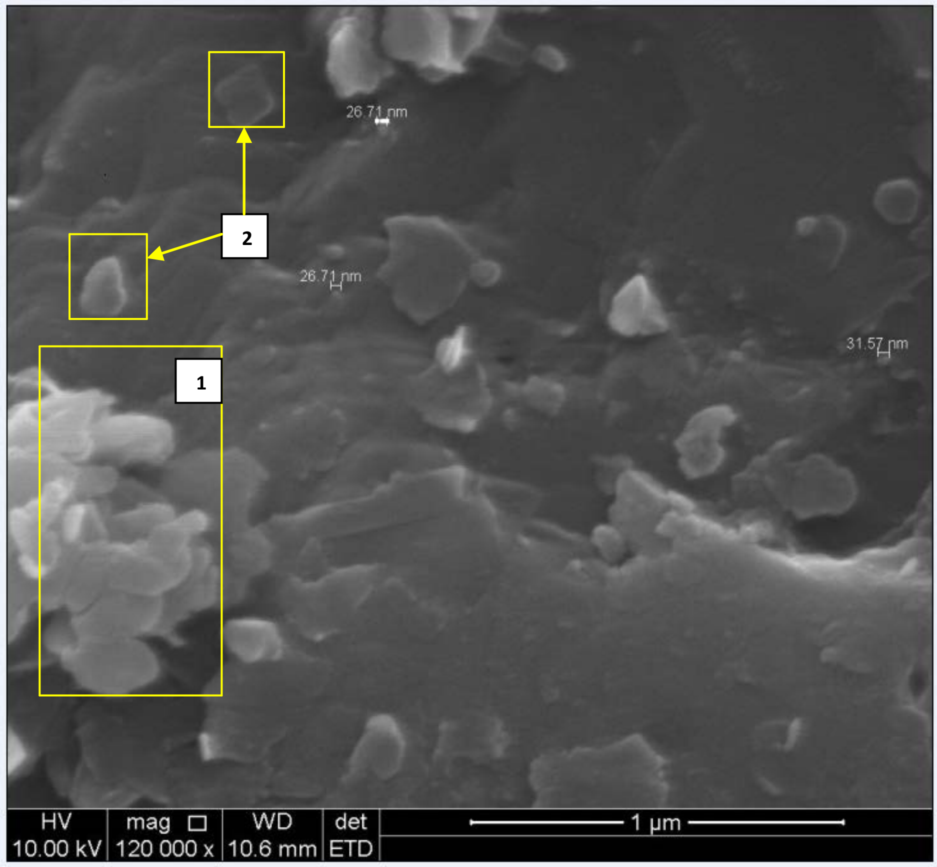

Figure 19: Electron microscopy photo of sub-micron particles from the blast hole drilling area at mine A. (1- agglomeration; 2- possible kaolinite disks).

Figure 20 illustrates an electron microscopy photo of the sub-micron particles from the drag line area at mine A. The majority of sub-micron particles seen in this photo are clinging to larger clay like structures. There are very few particles seen in this photo with a diameter smaller than 0.1 µm. The majority of these sub-micron particles have disk like shapes with irregular edges. This may indicate the presence of clay minerals and more specifically kaolinite. EDS analysis were not done because the sample was spatter coated with gold/palladium to make the nanoparticles visible.

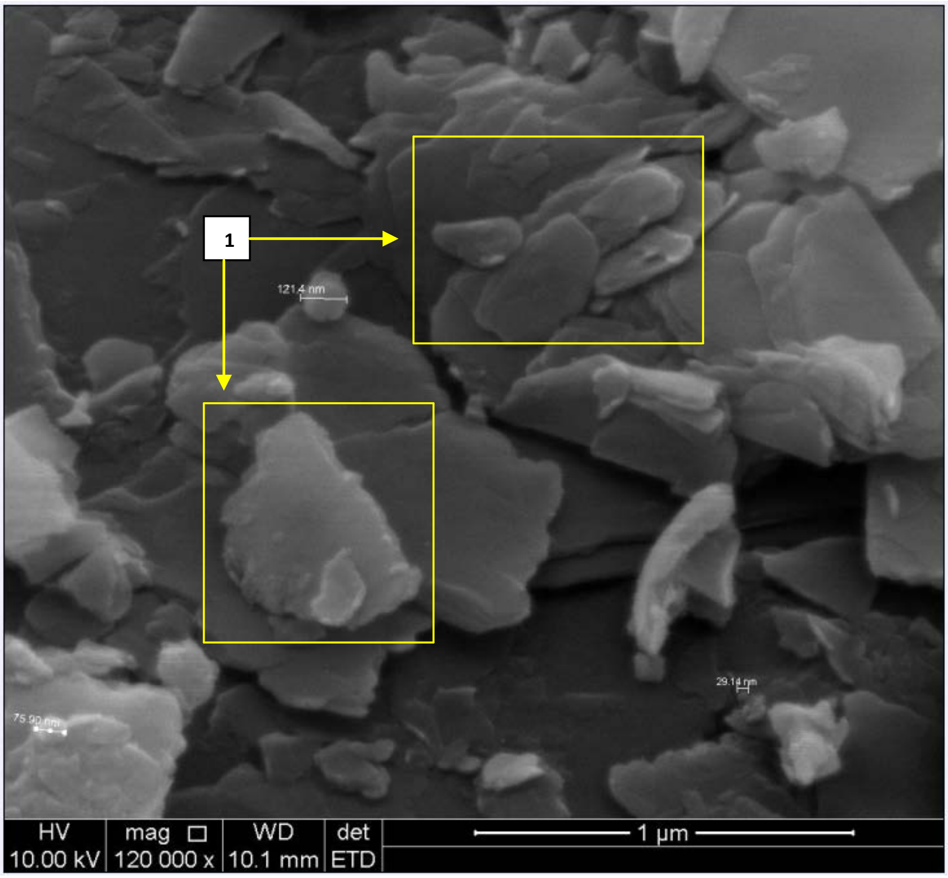

Figure 20: Electron microscopy photo of sub -micron particles from the drag line area at mine A (1- possible kaolinite disks).

Figure 21 illustrates an electron microscopy photo of the sub-micron particles from the blast hole drilling area at mine B. The majority of sub-micron particles seen in this photo are clinging to larger clay like structures. The smallest independent particles found are between 0.02 µm and 0.1 µm in diameter. Some of the nanoparticles are shaped more roundly while others have disk like shapes. The disk like shaped particles indicates the presence of clay minerals. Many of the smaller particles seem to be independent, but are in fact part of the larger particles. EDS analysis were not done because the sample was spatter coated with gold/palladium to make the nanoparticles visible.

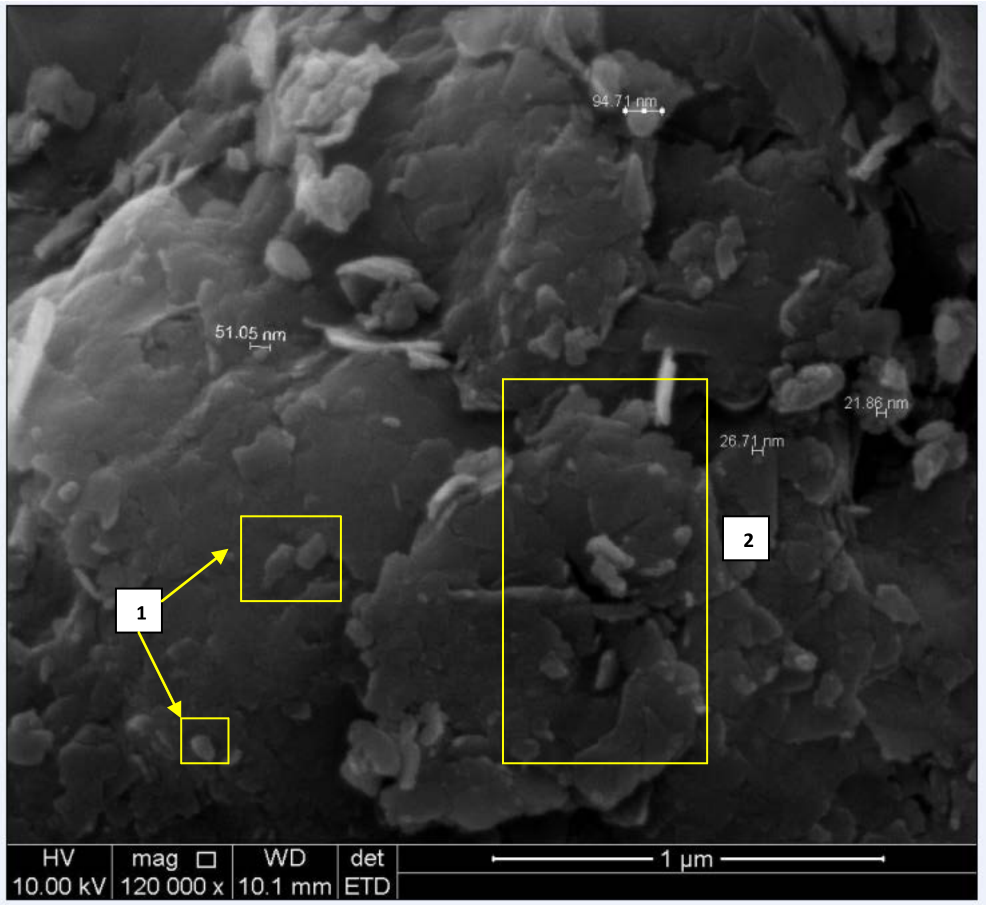

Figure 21: Electron microscopy photo of sub -micron particles from the blast hole drilling area at mine B (1- possible kaolinite disks; 2- agglomeration of sub-micron particles).

Figure 22 illustrates an electron microscopy photo of the sub-micron particles from the power shovel area at mine B. The majority of sub-micron particles seen in this photo are clinging to larger clay like structures. The smallest independent particles found are between 0.02 µm and 0.04 µm in diameter. The visible nanoparticles are roundly shaped and the presence of clay minerals is less when compared to the other opencast areas. Many of the smaller particles seem to be independent, but are in fact part of the larger particles.

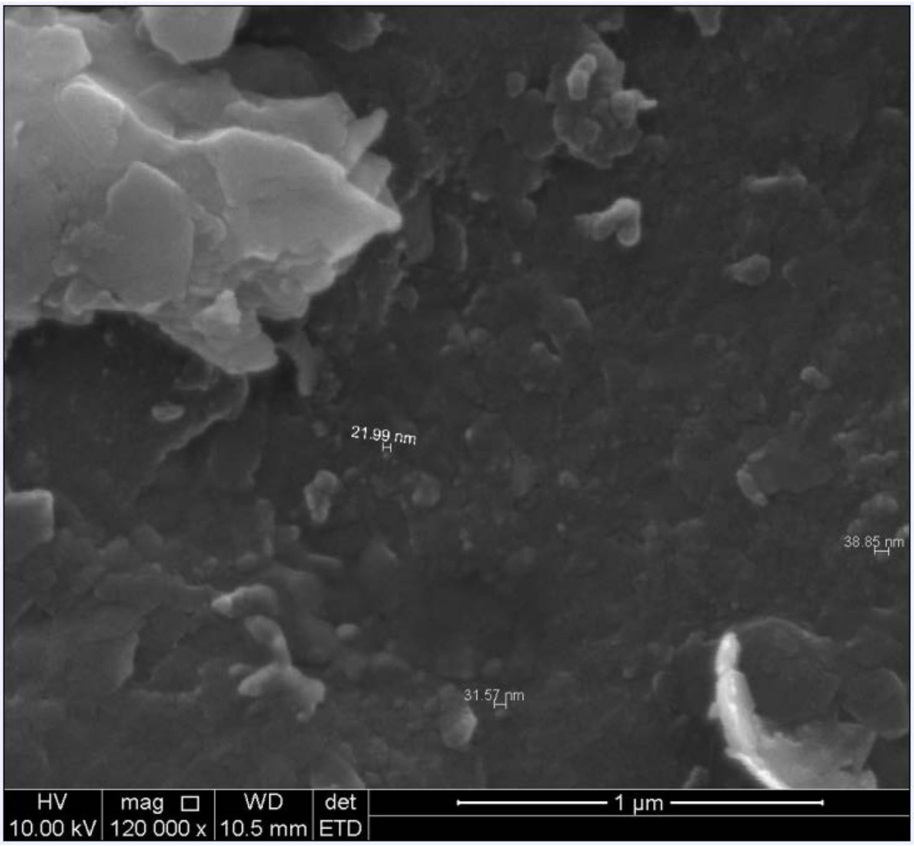

Figure 22: Electron microscopy photo of sub -micron particles from the power shovel area at mine B.

Figure 23 illustrates an electron microscopy photo of the sub-micron particles from the continuous miner and roof bolter areas at mine A. The electron microscopy photos of the two areas are very similar and thus only one is presented. The majority of sub-micron particles seen in this photo are clinging to larger clay like structures. The smallest independent particles found are between 0.02 µm and 0.05 µm in diameter. The visible nanoparticles are roundly shaped and there is very little evidence of clay minerals. It is clear that there are less visible nanoparticles found in the underground areas at mine A than at its opencast areas (Figure 19 and 20).

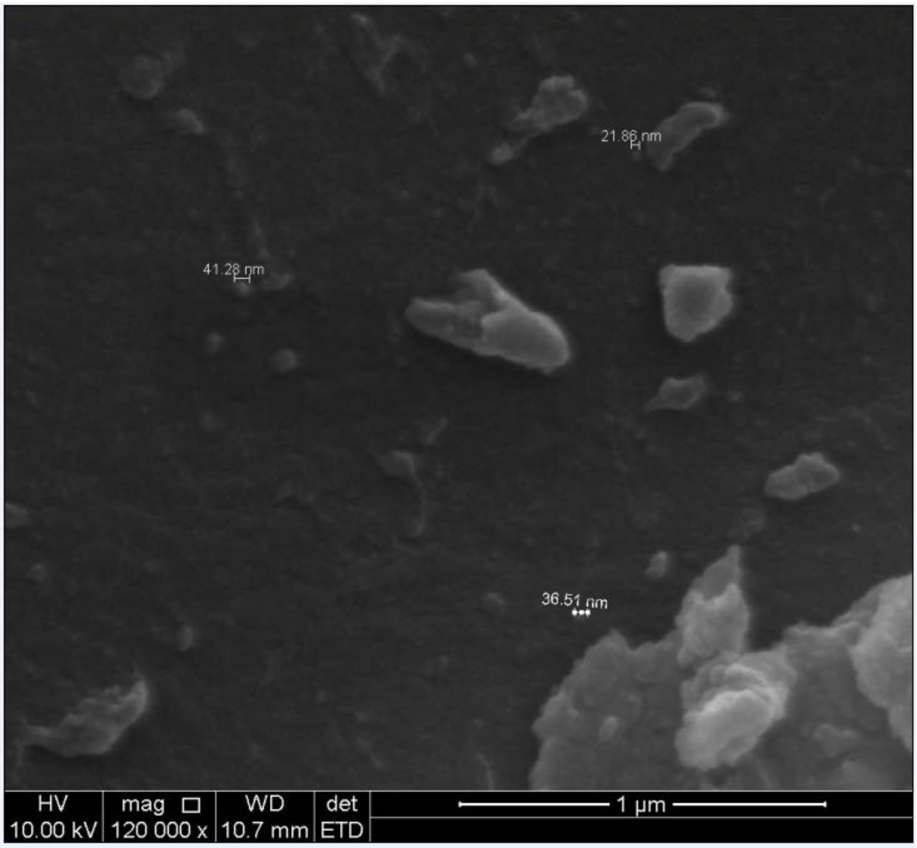

Figure 23: Electron microscopy photo of sub -micron particles from the continuous miner and roof bolter (underground) areas at mine A.

Figure 24 illustrates an electron microscopy photo of the sub-micron particles from the continuous miner and roof bolter areas at mine B. The electron microscopy photos of the two areas are very similar and thus only one is presented. The majority of sub-micron particles seen in this photo are clinging to larger clay like structures. The smallest independent particles found are between 0.04 µm and 0.1 µm in diameter. The visible nanoparticles are round in shape. It is clear that there are less visible nanoparticles found in the underground areas at mine B than at its opencast areas (Figure 21 and 22). It seems that the underground areas at mine B have more visible sub-micron particles when compared to the underground areas at mine A.

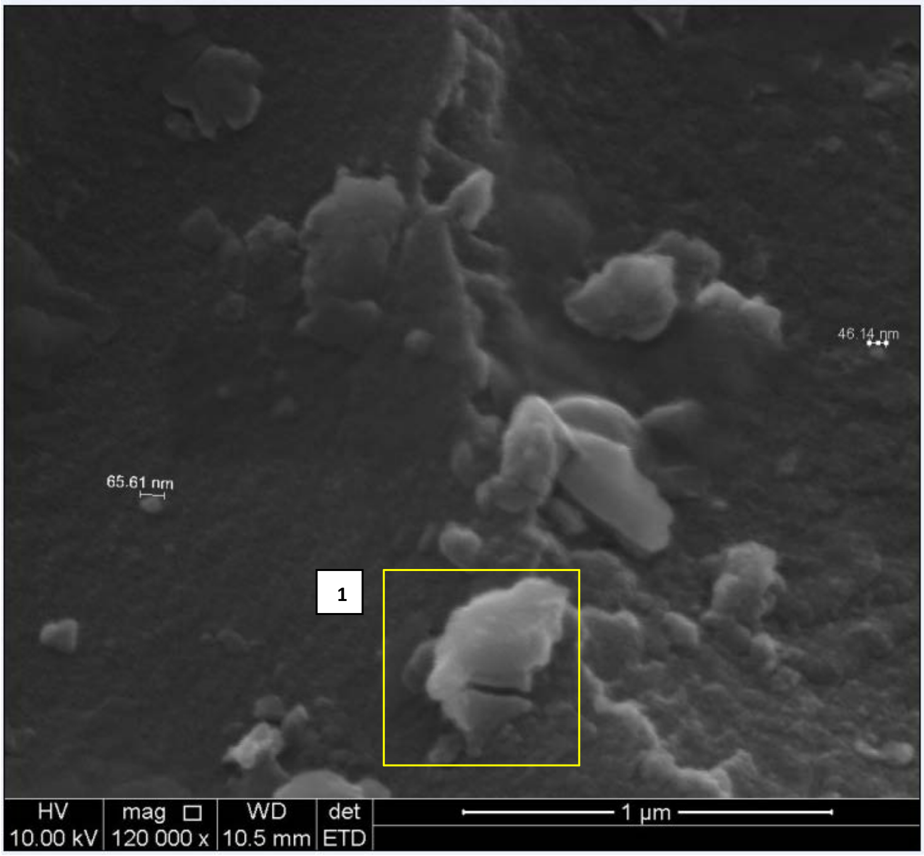

Figure 24: Electron microscopy photo of sub -micron particles from the continuous miner and roof bolter (underground) areas at mine B (1- possible clay mineral disks).

3.4 Discussion

3.4.1 The physical and chemical properties of inhalable coal dust from the different opencast areas at mine A

The average respirable and inhalable dust concentrations are depicted by Figure 4 and Figure 5. The average respirable dust concentration at the blast hole drilling rig was 0.486 mg/m^3 (σ = 0.62 mg/m^3) and the inhalable distribution 37.335 mg/m^3 (σ = 39.5 mg/m^3). The drag line area showed a respirable dust concentration of 0.224 mg/m^3 (σ = 0.29 mg/m^3) while its inhalable concentration was 23.194 mg/m^3 (σ = 26.8 mg/m^3). From these results it is clear that the concentrations of respirable and inhalable dust are much higher at the blast hole drilling area when compared to the drag line area. The CPC results (sub-micron particle counter) in Table 1 also show a much higher count of sub-micron particles (41913 x 10^6 more) at the blast hole drilling rig when compared to the drag line area. So, at the blast hole, more dust of all three size categories are formed than at the at the drag line. A probable reason for these observations is that the drilling activities grind the soil much finer than the drag line activities causing an increase in all three size categories.

When looking at the SEM photos from these areas (Fig 6 and 7) it can be seen that the majority of the inhalable particles are between 10 µm and 100 µm and are irregularly shaped with large surface areas. There is clear evidence of quartz in these two photos. Silica dioxide (SiO_2) is an oxide of silica and is most commonly found in sand or quartz (Rice, 2000). The majority of quartz particles in these images are larger than 50 µm and the more visible ones, larger than 100 µm. This is probably because silica is a very hard substance and therefore do not break into smaller particles easily. The size of the silica particles is tremendously important because of the health risk they may hold. It is also clear that there is fibre like particles present in these SEM photos. These fibres or splinters will have different aerodynamic properties when compared to other particles (Johnston *et al*., 1982) and will be deposited in different areas in the lung via different mechanisms than particles of other shapes. The disk like particles seen in Figure 7 are most likely kaolinite particles and as the fibrous particles these flat disks will have unique aerodynamic properties and lung deposit mechanisms when compared to more three dimensional particles.

The EDS analysis of the samples taken at the blast hole drilling rig and the drag line indicates that there is a higher concentration of carbon and silica at the blast hole drill when compared to the drag line while the drag line shows higher concentrations of aluminium (possible kaolinite) and iron (Fig 13). The reason for the higher carbon levels at the blast hole drill is because the rig drilled through the overburden layer into the coal seam causing the dust to have higher concentrations of carbon. The drag line where clearing an area where the coal seam had already been mined causing lower carbon concentrations in the dust, but with higher concentrations of impurities. The silica concentration is also higher at the drilling area because the drill can grind the hard quartz particles much finer (into inhalable particles) when compared to the drag line. Other minerals (excluding quartz and carbonaceous material) found in these dust samples when comparing the EDS analysis to Table 9 are kaolinite and illite because of the high concentrations of silica and aluminium as well as trace amounts of potassium and iron. The kaolinite plates are also clearly visible in Figure 7.

Figure 19 and Figure 20 represents the sub-micron particles found in the dust samples taken from the blast hole drilling area and the drag line at mine A. These images look quite different than expected when compared to Figure 6 and Figure 7 taken at much lower resolutions. There seem to be a lot more sub-micron particles in the samples taken from the drag line area when compared to the blast hole drilling area. The possible reasons for this will be discussed on page 76.

3.4.2 The physical and chemical properties of inhalable coal dust from the different opencast areas at mine B

The average respirable dust concentration at the blast hole drilling rig was 0.336 mg/m^3 (σ = 0.45 mg/m^3) and the inhalable distribution 40.689 mg/m^3 (σ = 43.77 mg/m^3). The power shovel area showed a respirable dust concentration of 0.268 mg/m^3 (σ = 0.31 mg/m^3) while its inhalable concentration was 37.690 mg/m^3 (σ = 42.1 mg/m^3). From these results it is clear that the concentrations of respirable and inhalable dust are much higher at the blast hole drilling area when compared to the power shovel area. The CPC measurements in Table 2 also show a higher count of sub-micron particles at the blast hole drilling rig (6597 x 10^6 more) when compared to the power shovel area. The difference in the CPC measurements is not as high as the difference recorded at the opencast areas at mine A. A probable reason for these observations is that the drilling activities grind the soil much finer than the power shovel activities causing an increase in airborne dust as well as sub-micron particles. More reasons will come to light after discussing the elemental properties of the different dust samples. It is also clear that the average inhalable dust concentrations were higher at mine B and the average respirable dust concentrations were higher at mine A’s areas (Fig 4 and 5).

When looking at the SEM photos from these areas (Fig 8 and 9) it is clear that the majority of the inhalable particles are between 10 µm and 90 µm and are irregularly shaped with large surface areas. Figure 8 (blast hole drilling dust sample) indicates much higher levels of agglomeration formations when compared with Figure 9. There is also clear evidence of quartz in these two photos. The majority of quartz particles in these images are larger than 50 µm and the reasons for this would be the same as previously stated. Figure 8 also indicates what seem to be kaolinite and illite particles. Kaolinite and illite are characterised by flat disk shaped particles adhered to one another forming a cylinder shaped particle (Altekruze *et al.,* 1984). There is also fibre like particles seen in Figure 8 which again will have unique aerodynamic properties when compared to other (more three dimensional) particles.

The EDS analysis of the samples taken at the blast hole drilling rig and the drag line indicates that there is a higher concentration of oxygen that are mostly bound to silica to form silica dioxide (Rice, 2000), silica, aluminium and potassium at the blast hole drill when compared to the power shovel, while the power shovel shows higher concentrations of carbon (Fig 13 and 14). The reason for the higher levels of impurities at the blast hole drill is because the rig drilled through the overburden layer to get to the coal seam while the power shovel was busy mining the already exposed coal seam. This would also explain why the carbon concentration at the power shovel is much higher than at the blast hole drilling rig. The main minerals found in the dust sampled at the blast hole drilling rig are quartz, kaolinite and illite after identifying the amounts of silica, aluminium, potassium and iron analysed. There may also be calcite and dolomite present when looking at the calcium concentrations found. The main minerals found in the dust sampled from the power shovel are carbonaceous material and quartz as well as kaolinite when looking at the amounts of carbon, silica and aluminium.

When looking at the sub-micron particles presented by Figure 21 and Figure 22, there are a lot more sub-micron particles and especially nanoparticles (smaller than 0.01 µm) from the blast hole drilling area when compared to the power shovel area. This seems strange when considering the CPC results of sub-micron particles from both areas that did not differ that much. The reason for this is that the majority of sub-micron particles in Figure 21 are part of larger structures due to agglomeration, while the CPC counts particles that are not agglomerated but free sub-micron particles.

3.4.3 The physical and chemical properties of inhalable coal dust from the different underground areas at mine A and mine B

The physical and chemical properties of dust from the underground areas at mine A and mine B are discussed together because of the similarities between these two underground mines.

The average inhalable dust distribution at the continuous miner at mine A was 57.840 mg/m^3 (σ = 64.7 mg/m^3). The roof bolter area at mine A showed a inhalable dust concentration of 45.325 mg/m^3 (σ = 53.1 mg/m^3). An inhalable concentration of 64.480 mg/m^3 (σ = 70.5 mg/m^3) was obtained at the continuous miner at mine B while the roof bolter area at mine B showed an inhalable concentration of 53.75 mg/m^3 (σ = 61.2 mg/m^3). It is clear from these results that the concentrations of inhalable dust are higher at the continuous miner than at the roof bolter areas. This contradicts the previous statements that the drilling activities produce much more inhalable dust. The fact of the matter is that the continuous miner grinds a much larger surface at any given time when compared to the roof bolter and thus producing enormous amounts of coal dust. Both the respirable and inhalable dust concentrations are higher at mine B (producing lower grade coal) when compared to mine A.

Figure 10 represents the inhalable dust from the underground areas at mine A and mine B. The SEM photos were very similar and so only one was presented. The majority of inhalable particles at the different underground mining activities are smaller than 30 µm and are irregularly shaped. There is also evidence of quartz particles smaller than 50 µm in these inhalable dust samples. The amount of inhalable dust particles is also much higher in the underground areas when compared to the opencast activities of the two mines.

The EDS analysis of the inhalable dust particles from the underground activities (Table 6) indicates that the carbon concentrations are slightly higher at the roof bolters than the continuous miners. The continuous miners on the other hand show higher concentrations of impurities such as quartz when compared to the roof bolter areas (Fig 15 and 16). The dust samples from the roof bolter and continuous miner at mine A also show higher carbon concentrations with fewer impurities when compared to mine B. This is to be expected because mine A produces higher grade coal than mine B. The main minerals found in these inhalable dust samples are carbonaceous material, quartz and kaolinite when comparing the amounts of carbon, silica and aluminium in these samples. There is a small percentage of calcium found in these samples. The main cause for this is the stone dust that is sprayed against the walls and ceiling to suppress airborne coal dust concentrations and lower the possibility for a coal dust explosion. The stone dust is mostly comprised of calcium oxide and other none combustible substances (Cain, 2003).

3.4.4 The physical and chemical properties of respirable coal dust from the different underground areas at mine A and mine B

The average respirable dust concentration at the continuous miner at mine A was 3.17 mg/m^3 (σ = 3.32 mg/m^3) and the respirable dust concentration at the roof bolter was 1.323 mg/m^3 (σ = 1.42 mg/m^3). The respirable dust concentration at the continuous miner at mine B was 2.806 mg/m^3 (σ = 3.07 mg/m^3) while the respirable dust concentration at the roof bolter was 1.225 mg/m^3 (σ = 1.28 mg/m^3). Again it is clear that the respirable dust concentrations are higher at the continuous miner than at the roof bolter areas. The respirable dust concentrations are also higher at the underground areas of mine A when compared to mine B

Given in Figure 11 is the respirable dust from the continuous miner areas at mine A and mine B. The majority of particles are smaller than 10 µm but there are a few that are larger than 10 µm. The particles larger than 10 µm are carbonaceous in nature and their larger size is not attributed to agglomeration. The majority of particles seen in Figure 11 have irregular shapes with sharper edges, especially the identified silica particles. Figure 12 represents the respirable dust particles from the roof bolter operations at mine A and mine B. All of the particles are between 0.4 and 6 µm in diameter and also have irregular shapes with sharp edges. Again the presence of silica particles can be seen but in fewer numbers when compared to the inhalable particles from the opencast and underground areas. It is clear that the respirable particles from the roof bolter areas are smaller when compared to the respirable particles from the continuous miners. Again the reason for this is because the drilling operations grind the coal dust much finer than the continuous miner does.

The EDS analysis of the respirable dust particles from the underground activities (Table 7 and 8) indicates that the carbon concentrations are slightly higher at the roof bolters than at the continuous miners. There are also fewer impurities found in the samples from the roof bolters when compared to the continuous miner samples (Fig 17 and 18). Again the carbon concentrations found in the respirable samples from mine A are higher than that of mine B. The main minerals found in these respirable dust samples are carbonaceous material and quartz when considering the amount of carbon and silica found in these samples. When comparing the EDS results of the respirable and inhalable dust from the underground areas, it is clear that the respirable dust samples contain higher concentrations of carbon with fewer impurities when compared to the inhalable dust samples.

Figure 23 represents the sub-micron particles from the roof bolter and continuous miner areas at mine A while Figure 24 represents the roof bolter and continuous miner areas at mine B. There seem to be less independent sub-micron particles and especially nanoparticles (smaller than 0.1 µm) in the samples taken from the underground areas at mine A when compared to mine B. The sub-micron particles (between 0.1 µm and 1 µm) in these two images have irregular shapes with sharp edges. Figure 24 do have some disk like particles which is most likely part of clay minerals. The visible nanoparticles (on the SEM photos) on the other hand seem to have more spherical shapes.

3.4.5 Discussion on the presence of visible sub-micron particles

One of the questions arising from this pilot study is: What is the presence of visible sub-micron particles in some area dust samples compared to others. It is unexpected that the number of visible sub-micron particles is less in certain samples despite the fact that other results such as the CPC readings indicated high concentrations of sub-micron particles. According to the gravimetrical results, the CPC results (Table 1) and the lower definition SEM photos (Fig 19 and 21), the amount of sub-micron particles in the SEM photos should be high at the drilling area when compared to the drag line area. The sub-micron particle photos however do not mirror this conclusion and show fewer free sub-micron particles were present at the blast hole drill. The same scenario is seen at the opencast areas of mine B. According to the gravimetrical and CPC results (Table 1), the number of sub-micron particles is expected to be higher at the power shovel but again the photos indicate that only a small number of free sub-micron particles were present. The same is true for the underground areas of mine A and mine B where it is expected that the number of sub-micron particles should be roughly the same in the different areas. SEM photos of these sub-micron particles however indicated that the underground areas of mine B have more visible sub-micron particles when compared to the underground areas at mine A (Fig 23 and 24).

When studying the results from the blast hole drilling and the drag line areas at mine A it is clear that the gravimetrical results for respirable particles (smaller than 10 µm) and especially the CPC results indicated that there are a far greater amount of sub-micron particles than the SEM photos showed. According to the EDS analysis of these two area samples the dust from the drilling area contained more carbon (33.5%) with less impurities when compared to the drag line area (26.2%). Similar results is seen at the opencast areas of mine B where the CPC results (Table 1) showed quite similar measurements between the blast hole drilling area and the power shovel. Again a subjective interpretation of the SEM photos indicated less sub-micron particles at the power shovel area when compared to the drilling area. The EDS analysis indicated a much higher concentration of carbon in the dust from the power shovel (61.5%) compared to the dust from the drilling rig which had more impurities and a low carbon (11.9%) concentration. Sub-micron photos from the underground areas also indicate that the areas with a higher carbon concentration (mine A) seem to have fewer sub-micron particles when compared to areas with a lower carbon concentration (mine B).

All these results may indicate that the majority of the sub-micron particles visible on the SEM photos from the areas with higher concentrations of impurities are in fact part of larger structures due to agglomeration and that these sub-micron particles are more prone to form agglomerations in dust contaminated with more impurities. The sub-micron particles in dust with a higher carbon concentration do not seem to form agglomerations easily and are therefore probably able to fall off the larger particles making them more challenging to collect. Again the CPC counts particles that are not agglomerated but free sub-micron particles. This could indicate that the number of free sub-micron particles may be higher at areas where the carbon concentrations are higher. This corresponds with findings made by Srikanth *et al*. (1995) as well as Attfield and Seixas (1995).

3.4.6 Potential hazards that the characterised coal dust may hold

Potential for an underground coal dust explosion

From the results gathered, the chance of a coal dust explosion is very slim. The minimum explosive concentration (MEC) is the smallest amount of dust suspended in a cloud that will explode when ignited. The MEC varies with regards to the fineness of the dust, the volatile content and also the presence of methane gas. Recent studies on modern underground coal mines concluded that the MEC is approximately 50 g/m^3 (50 000 mg/m^3) (Cain, 2003). The highest dust concentration (with particles smaller than 100 µm) was 64.5 mg/m^3 sampled at the continuous miner at mine B. This concentration is far less than what is necessary for a coal dust explosion to occur. It should however be noted that the explosive risk increases as the particle size decreases. A decrease in particle size will lead to a decrease in the necessary concentration of dust for a coal dust explosion to occur.

Potential hazardous health effects

The SEM results from the opencast areas at mine A indicate that the majority of visible airborne particles on the SEM photos are between 100 µm and 10 µm. According to Figure 3 between 60% and 80% of these particles will be deposited in the nasal, pharynx and larynx pulmonary regions. CPC results indicated that there was a far greater number of airborne sub-micron particles at the blast hole drilling area (69 256 x 10^6 particles per m^3) compared to the drag line area (27 343 x 10^6 particles per m^3). Between 10% and 50% of these particles will be deposited in the alveolar region where the pulmonary health risk is the greatest. Several studies have indicated that sub-micron particles produce significantly greater inflammation and interstitial translocation (Ferin *et al.,* 1991; Oberdörster *et al.,* 1992). The pulmonary clearance of these sub-micron particles is also significantly slower when compared to larger particles (Oberdörster *et al.,* 1994). According to the results the majority of particles reaching the alveoli will be carbonaceous in nature because the impurities are prone to form large agglomerations and therefore decrease its chances of reaching the alveoli. The higher the concentration of carbon particles reaching the alveoli, the greater the chances become of contracting coal workers' pneumoconiosis (Parkes, 1994). Geiser *et al.,* (2002) found that all of the different sized particles (with different compositions) deposited in the alveoli will be coated with an aqueous lining layer where macrophage cells will proceed to engulf them. Polymorphonuclear leukocytes will be stimulated by these particles and may release reactive oxygen species (ROS), which can result in tissue damage and injury (Prahalad *et al.,* 1999).

The SEM results from the opencast areas at mine B also indicate that the majority of particles are between 100 µm and 10 µm. According to Figure 3 (Oberdörster, 2001) between 60% and 80% of these particles will be deposited in the nasal, pharynx and larynx pulmonary regions. The CPC results indicate that there is a larger number of sub-micron particles from the blast hole drilling area (57 008 x 10^6 particles per m^3) when compared to the power shovel area (50 411 x 10^6 particles per m^3). Between 10% and 50% of these sub-micron particles will be deposited in the alveolar region (Oberdörster , 2001). The majority of these sub-micron particles from the power shovel area are carbonaceous in nature according to Table 5. The sub-micron particles from the blast hole drilling area will contain a lot more impurities of which silica is the greatest concern. Silica particles are known for their ROS contribution (Rice, 2000) and when considering the study done by Geiser *et al*. (2002), this is quite alarming because these deposited sub-micron silica particles will all be engulfed. This will enhance the possibility of developing Silicosis which increases the chances for tumour formation in the pulmonary system as well as systemic damage because of the extreme small size of these particles (Tjälve and Henriksson, 1999; Brenneman *et al*., 2000; Dorman *et al*., 2002). There is alarmingly high concentrations if silica found at the opencast areas (Tables 2, 3 and 4), but due to their large size the majority of these particles will not reach the alveoli thus limiting the risk of silicosis (Oberdörster, 2001).

The inhalable dust SEM results from the underground areas at both mine A and mine B indicate that the airborne particles are between 100 µm and 1 µm in size. Figure 3 indicates that between 60% and 30% of these particles will be deposited in the nasal, pharynx and larynx pulmonary regions and 10% of the particles between 4 µm and 1 µm will be deposited in the alveolar region. The respirable SEM results indicate visible particle sizes ranging between 10 µm and 0.5 µm. Between 80% and 50% of the particles ranging from 1 µm to 10 µm will be deposited in the nasal, pharynx and larynx pulmonary regions. 10% to 15% of the particles between 1 µm and 0.5 µm will be deposited in the alveolar regions. The percentage of particles between 0.1 µm and 0.01 µm that will be deposited in the alveolar region ranges from 20% to 50% (Oberdörster, 2001). The majority of particles from the underground mining activities reaching the alveoli are carbonaceous in nature. Even though the percentage of impurities such as silica is low, the carbonaceous particles still hold a real threat because of the coal workers' pneumoconiosis and progressive massive fibrosis it may cause (Parkes, 1994).

Some of the nanoparticles found in this study are between 0.02 µm and 0.03 µm in diameter. These particles can easily go through the wall of the alveoli and enter the blood stream to interact with various cell components (nucleus, mitochondria, etc.). Some of these particles such as Fe and Si are not soluble, but because of their extreme small size they can easily enter living cells. Freshly ground dusts or silica particles are more inflammatory than aged crystals because of the greater generation of silica-derived free radicals in these materials where surface ROS are formed (Fubini and Hubbard, 2003). Fubini and Hubbard (2003) also found that the cellular response or ROS formation is enhanced when the silica is contaminated with iron as found in the opencast areas of mine A and mine B. As stated earlier it seems that the sub-micron particles of the samples with more impurities are more visible due to agglomerations formed. It is then possible that many of the carbon and even silica nanoparticles will not form part of these agglomerations and penetrate even further into the respiratory system. According to this argument there will be more nanoparticles reaching the alveoli in the areas where the impurity levels are lower or the areas with much purer coal. Previous research also indicated that the higher the rank or quality of coal, the greater the risk of contracting the more developed stages of coal workers' pneumoconiosis and progressive massive fibrosis (Fubini and Hubbard, 2003). In the higher ranking coal, there may be a greater relative surface area of the coal dust particles, higher surface-free radicals and higher silica content (Phillips and Belle, 2003). Silica exposure and hence silicosis is more common in mines with a high grade of coal (Attfield and Seixas, 1995) and in workers such as roof bolters who work outside of the coal seams in quartz-containing rock (Buchanan *et al.,* 2003). This could indicate that because there are more free sub-micron particles in the mines with higher grade coal (such as mine A) the chance of contracting Coal workers pneumoconiosis, Siderosis and Silicosis increases.

3.5 Conclusion

It is possible to identify the majority of physical and chemical characteristics of coal dust by means of gravimetric analysis and improved methods such as particle counting, scanning electron microscopy and energy dispersive X-ray spectroscopy if sufficient airborne dust is collected. There were differences found, regarding the morphological; chemical and physical characteristics, between the different opencast and underground areas. The dust from the opencast areas differed because of the different areas where the mining activities took place. The carbon concentrations were low (with higher concentrations of impurities) at the blast hole drilling and drag line mining areas because of the overburden covering the coal seam. Mining areas such as the power shovel yielded higher concentrations of carbon because the coal seam had already been exposed. The dust from the areas with higher concentrations of impurities consisted of different minerals and small particles seemed to be more prone to the formation of agglomerations when compared to areas consisting of higher carbon concentrations. The majority of the particles from the opencast areas were between 100 µm and 10 µm in diameter, most of which had irregular shapes. The presence of quartz particles were identified at the opencast areas and it was determined that the majority of these particles were larger than 50 µm because it is not easily broken down into smaller particles. The CPC measurements indicated that the majority of airborne sub-micron particles were found at the blast hole drilling operations because of the drill's capability to grind the dust much finer. There was also a high concentration of sub-micron particles found at the power shovel because of the lesser degree of agglomeration.

There were also differences seen between the dust samples from the underground and opencast operations. The carbon concentrations from the underground dust samples were much higher (with lower concentrations of impurities) when compared to the opencast areas because there they were directly mining into the coal seam. The carbon concentrations were slightly higher (with fewer impurities) at the underground areas of mine A when compared to mine B which were to be expected because mine A produces a higher grade coal than mine B. The gravimetrical results indicated that the underground areas had much higher concentrations of airborne dust due to the confined space of the underground mining environment compared to the open air environment at the opencast areas. The sizes of the inhalable and respirable particles tend to shift more to the smaller sizes at the underground areas when compared to the opencast areas because of the higher carbon concentrations and fewer agglomeration formations. The respirable dust from the underground areas at mine A were also slightly finer when compared to the respirable dust from mine B due to the higher carbon concentrations at mine A.

According to the underground dust concentrations the chances for a coal dust explosion is slim but still remains a threat that must be monitored. It was seen that the majority of airborne particles from mining areas with higher concentrations of impurities formed agglomerations and because of their size, will be mostly deposited in the nasal, pharynx and larynx pulmonary regions. The mining areas with a higher concentration of carbon saw a higher amount of respirable and sub-micron particles that can be deposited in the alveolar regions of the pulmonary system. It would seem that the respiratory threat is greatest in the areas where there are higher concentrations of carbon and as a result more sub-micron particles. Studies done by Fubini and Hubbard (2003) as well as Attfield and Seixas (1995) seem to agree with these observations. The opencast areas where there are higher concentrations of silica and higher measured levels of sub-micron particles probably hold health threats. Even though the formations of agglomerates are prevalent in these areas, there are still a large amount of free sub-micron particles which could include silica.

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CHAPTER 4

CONCLUSION

4.1 Discussion and Conclusion

It is possible to identify the majority of physical and chemical characteristics of coal dust by means of gravimetric analysis and improved methods such as particle counting, scanning electron microscopy and energy dispersive X-ray spectroscopy. There were differences found between the various opencast and underground areas at mine A and mine B with regard to the morphological, chemical and physical characteristics.

There were various dissimilarities with regard to the characteristics of dust at the opencast areas as a result of the type of mining activity taking place as well as the amount of overburden present at that specific mining area. This can clearly be seen when comparing the blast hole drilling areas, which had a large amount of overburden with more impurities, with the power shovel area where the overburden had already been removed and coal mining had commenced.

There were also differences seen regarding the particle size and amount of agglomeration depending on the purity of the coal dust at the opencast areas. Pertaining to agglomeration, it seemed that the dust samples containing higher amounts of impurities, with low levels of carbon such at the drilling areas, were more prone to form agglomerations. This can also be seen when looking at the sub-micron particle photos where it seems that the particles from the drilling and drag line areas (with high impurity levels) form part of agglomerations. There was also evidence of fibre like particles in some of the opencast dust samples. It is important to note because these fibre particles will behave differently (aerodynamically) when compared to more three dimensional particles (Johnston *et al.,* 1982). The same is true for the clay disk particles found in the dust samples.

The underground dust samples indicated much higher inhalable and respirable concentrations when compared to the opencast areas because of the confined area as well as the higher carbon concentrations (Organiscak and Page, 1999). The underground areas also indicated much higher concentrations of carbon, with fewer impurities, when compared to the opencast areas. The average particle size at the underground areas were also much smaller when compared to the opencast areas and this is supported by the findings of Srikanth *et al*. (1995) who stated that the respirable dust concentration increases with coal grade (carbon concentration). It was also clear that the particles produced at the roof bolter operations were finer than those produced at the continuous miner operations at the underground coal mines.

When looking at the sub-micron particles this study found some interesting and even controversial results. At the opencast areas, CPC results indicated that the blast hole drilling operations produced much more sub-micron particles when compared to the drag line and power shovel operations. The SEM results however indicated that there are more visible sub-micron particles at the areas with higher levels of impurities. There are also very few visible sub-micron particles from the power shovel area which contradicts the CPC measurements at this area. The underground areas which have higher carbon concentrations also indicated fewer visible sub-micron particles when compared to areas with higher levels of impurities. According to Strikanth *et al*. (1995) and Moore and Bise (1984) the amount of respirable dust particles (and therefore sub-micron particles) increases as the purity of coal increases which contradicts the above mentioned SEM results. A probable reason for this is that the impurities are more prone to form agglomerations thus giving the illusion that there are less visible sub-micron particles at the areas with higher carbon concentrations. The CPC results also indicated that there are more sub-micron particles in areas with higher carbon concentrations further backing the notion that the amount of respirable dust increases as the purity of the coal increases.

4.1.1 Addressing of Hypothesis

As stated in Chapter 1 there were differences in the physical and chemical characteristics of dust produced at different coal mines and mining areas, thus proving the hypothesis to be correct.

Dust concentrations differed between the opencast as well as underground operations. The size and shape of the dust particles at the opencast areas were similar except for the areas with higher levels of impurities which were prone to form agglomerations. The average inhalable and respirable particle sizes at the underground areas were smaller than those found in the opencast areas. The results from the roof bolter also indicated smaller sized particles when compared to the continuous miner underground areas The EDS results indicated much higher levels of impurities (as a result of the overburden composition) at the opencast activities when compared to the underground areas where the pure coal seam were mined.

At the opencast areas the blast hole drilling operations did indicate higher concentrations of respirable dust when compared to the drag line and power shovel operations as stated in Chapter 1. The reason for this is because the drilling activities grind the dust much finer than the other opencast operations and therefore produces higher concentrations of respirable dust. The underground areas did indicate that the roof bolter areas produced smaller sized particles when compared to the continuous miner operations. It is clear however that the concentrations of respirable dust concentrations were higher at the continuous miners than at the roof bolters. The reason for this is the mere amount of dust produced at these two areas. The continuous miner grinds a much larger surface of the coal seam with its steel drum when compared the drill area of the roof bolter, thus producing much higher inhalable as well as respirable dust concentrations.

When looking at the coal purity it is difficult to compare the results from the opencast areas because of the different mining activities and different levels of overburden covering the coal seams at mine A and mine B. The blast hole drilling areas however indicated higher carbon levels at mine A when compared to mine B. The underground areas gave more clear indications regarding the dust carbon concentrations from the different activities. Both the continuous miner and roof bolting operations at mine A produced dust with higher carbon concentrations (with fewer impurities) when compared to mine B. It was known beforehand that mine A produces purer coal than mine B and these results supports this statement.

It can thus be said that the dust from the various coal mines and areas differs in their physical, chemical and morphological characteristics. The hypothesis stated in Chapter 1 was proven to be correct. This descriptive pilot study did indeed shed light on the possibility of characterizing coal dust with improved methods and also gave fascinating as well as unexpected insights about the differences in dust characteristics between different mining areas. It is now strongly recommended that a quantitative study be done where each mining area is studied in detail to better understand some of the fascinating discoveries made.

4.1.2 Potential Hazards and Health Effects

According to the results obtained during this pilot study, the chances for an underground coal dust explosion is very slim at mine A and mine B. Cain (2003) stated that the minimum explosive concentration of coal dust is approximately 50 000 mg/m^3 which is far more than the airborne dust concentrations measured at mine A and mine B.

The potential health effects are more of a concern with regards to airborne dust from the different mining areas. The major concern at the opencast areas is the presence of large amounts of quartz especially at the blast hole drilling and drag line operations. Because quartz is a hard material, it will not be easily broken down. That is why there are higher concentrations of silica in the dust samples from the blast hole drilling areas because of the drill's ability to grind the quartz much finer. Because of the decreased quartz particle size, the chances for developing Silicosis increases drastically (Tjälve and Henriksson, 1999;

Brenneman *et al.,* 2000; Dorman *et al.,* 2002). The majority of particles from the underground mining activities reaching the alveoli are carbonaceous in nature. Even though the percentage of impurities such as silica is low, the carbonaceous particles still hold a real threat because of the coal workers' pneumoconiosis and progressive massive fibrosis it may cause (Parkes, 1994). Previous research also indicated that the higher the rank or quality of coal (with more respirable and sub-micron particles), the greater the risk of contracting the more developed stages of coal workers pneumoconiosis and progressive massive fibrosis become (Fubini and Hubbard, 2003). This could indicate that because there are more sub-micron particles in the mines with higher grade coal (such as mine A) the chances of contracting coal workers pneumoconiosis, progressive massive fibrosis and Silicosis increases.

4.1.3 Challenges in This Study

The main shortcoming was the fact that there are very little literature available and studies done about characterization of certain aspects of dust and no previous studies on full characterization of dust. This is why this pilot study was so ambitious and the findings made may influence future studies.

Data gathering was burdened by numerous spoiled samples mostly due to the sampling pumps failing to operate for the required sampling time. Because the IOM, Cyclone and CPC measurements were conducted at the same time to investigate correlations, failure of one instrument spoiled the entire sampling train. Another particle counting instrument, the optical particle counter, could not be used due to an unexpected malfunction.

Environmental issues included changing wind directions at the opencast areas influencing the amount of dust the IOM samplers captured. The sampling was depended on where the specific mining activities took place during the course of the study and this caused difficulties to measure the exact same areas at the different mines. An example of this is the drag lines at mine B that received maintenance during the course of the survey. The amount of overburden at the opencast areas differed between the two mines making it difficult to accurately compare the opencast area results.

The tape used for the electron microscopy is normally carbon tape. Because coal dust was analysed, copper tape was used. Copper tape is not as effective as carbon tape because the copper heats up in a very short time frame which negatively influenced the quality of the photos and shortened the time spent to investigate each sample.

Financial limitations also influenced the amount of samples taken and the analysis thereof. The sampling equipment used was sufficient although more specialised equipment (such as low pressure impactors) would give more precise results, especially on the capturing and analysis of different sized particles (Dekati®, 2010). These instruments are however extremely expensive.

4.1.4 Future Investigations on Characterisation of Coal Dust

Future studies on the characterisation of coal dust may be improved by approaching the following aspects differently:

It is strongly recommended that more samples and measurement be taken at each mining activity to improve the accuracy of the results.

A larger number of mining areas can be samples to indicate all the differences in dust characteristics at coal mining operations.

There are sampling instruments that could give more detailed results. Low pressure impactors can be used to capture a vast range of different sized particles. These instruments are capable of dividing particle sizes in 13 categories, making it possible to better characterise the chemical and physical characteristics of different sized dust particles (Marjamäki *et al.,* 2000). The instrument that can be used is a Dekati® Low pressure impactor (DLPI).

4.1.5 Possible Future Studies

This study raised a few important questions that can be more clearly answered by conducting the following studies:

- Is coal dust with higher concentrations of impurities (and therefore lower concentrations of carbon) more prone to form agglomerations, thus limiting the amount of free sub-micron particles?
- Studies to identify why the grade or purity of coal influences the amount of respirable and sub-micron particles in coal dust.
- Determining the concentrations of respirable and sub-micron quartz particles at the different mining operations using low pressure impactors that are capable of capturing a vast range of different sized particles.

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