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COAL CHARACTERISTICS THAT LEAD TO ABRASION DURING GRINDING

MONNAMME TITUS TLOTLENG

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

Johannesburg 2011

Declarations

I declare that the contents of this research report are legitimate and are my own unaided work. This work is submitted for the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. I also confirm that this work has not been submitted for any degree or examination in the University, and all sources used are acknowledged by means of referencing.

……....

…….day of …….year……

Abstract

Currently in South Africa there is no acceptable standard method for testing coals for abrasion. Abrasion is the tendency of coals to wear away machinery. The technique referred to as YGP (Yancey, Geer and Price), proposed and accepted in 1951, is most commonly used to test for abrasion. Over the years there have been some modifications to this method by both mining houses and coal users (such as Eskom) which have resulted in inconsistent and conflicting results. To this end, this study serves as part of a larger project that will aim at devising a standard method acceptable for testing coals for abrasion in South Africa. The underlying principle behind this research was to determine the main characteristics in South African run of mine (ROM) coals that may cause abrasion. This research work specifically seeks to: (1) determine if the Abrasion Index (AI) and Hardgrove Grindability Index (HGI), empirical correlations, developed by Scieszka (1985), can be verified using experimental results; (2) determine if excluded minerals and included minerals are equally abrasive; (3) establish the type of abrasive wear that occurred during coal grinding.

Five ROM coals from the Witbank Coalfields were analysed. An abrasion index tester pot and Hardgrove machine were used to determine the grinding properties of the coal samples. XRD (Rietveld method), XRF, Petrography and SEM-EDS were used to characterise the coals samples in terms of their inorganic and organic components. SEM-EDS was also used for the particle morphology analysis, and blade surface topography analysis. TGA, moisture oven and sieve method were used for proximate analysis, moisture analysis, and particle size distribution analysis respectively.

The results indicated that the key characteristics that influenced the AI of the coal samples were moisture, vitrinite, and minerals and mineral associations (excluded and included minerals and carbominerite) and HGI. Results indicated that coal weathering renders coals less abrasive, compared to unweathered coals. It was concluded that AI and HGI are experimentally dependent; excluded and included minerals were equally abrasive; and three-body abrasive wear was established to be the main wear during grinding in an abrasion index tester pot.

Dedications

In memory of my mother

Popo Tsetsa Dorah Tlotleng

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Nomenclature

AI	abrasion index (mg kg^{-1})
AF	abrasion factor (mg kg^{-1})
B	tribological properties of grinding systems
CAC	coal abnormal conditions
EI	energy input (J)
f	function of
F	mass of the feed of particular size modulus (g)
G	grindability of coal within defined system
HGI	Hardgrove Grindability Index
IA_i	intensity of abrasion (mg m^2 s^{-l})
IC	index of comminution (mg J^{-1})
m	moisture
M	mechanical properties of coals
M_0	free moisture (%)
M_1	initial weight of the blades (g)
M_2	final weight of the blades (g)
ΔM	weight difference (mg)
n	normal force (N)
P	mass of the product of particular size modulus (g)
PC	pulverized coal < 75 µm (g)
q	mechanical and geometrical characteristics of hard particles
ROM	run of mine
R^2	radius of the abrasion index tester pot (m)
rpm	revolution per minute
rev/s	revolution per second
S	area of the blades exposed to materials during grinding (m)
SD	standard deviation
SEM-EDS	scanning electron microscopy with energy dispersive X-ray
TGA	thermal gravimetric analyser
T1/T2	temperature (°C)

ΔT	change in temperature
t_d	time a grinder takes to complete 12000 rev (s)
W	work index (J g^{-1})
W1	mass of bucket filled with un-dried coals
W2	mass of bucket filled with air dried coals
W3	mass of empty bucket
W_i	work index (J g^{-1})
WR	wear resistance (MJ g^{-1})
ΔW	M_1-M_2 (g)
X	inherent moisture (%)
XRD	X-ray diffraction
XRF	X-ray fluorescence
^oC	degree Celsius
Θ	temperature
Θ	number of revolutions (rev)
α	angular acceleration (m s^{-2})
ω	angular velocity (rpm)
$\boldsymbol{\tau}$	average integral value of torque (Nm)
ρ	porosity of coal
$\acute{\eta}$	overall efficiency of the grinding system
2Π	single complete revolution

CHAPTER 1: INTRODUCTION

Coals are naturally formed fossil fuels with many different characteristics. Coals are mainly made up of organic and inorganic matter. One important quality of coal is its burning characteristic, which is induced primarily by its organic matter. Owing to this characteristic, coals are used for different purposes, such as gasification, combustion and in the metallurgical process in South Africa and elsewhere. Typically, electricity is generated from steam turbines in power plants. The turbines are mechanical devices which utilise the thermal energy from steam produced through coal combustion. This is a process in which mechanical energy is converted into electrical energy according to the first law of thermodynamics. Combustion is a chemical reaction in which carbon (coal) reacts in excess oxygen (O_2) to produce steam (H_2O) and carbon dioxide (CO_2). This reaction is exothermic. For the maximum use of the coals fed into a combustion zone, they must be reduced such that their surface area is maximised.

For the boiler to efficiently combust coals, coals are reduced from lump size to small pulverised fuel (pf) size. Maximum surface area in combustion facilitates the burning character of the fuel. This size reduction is achieved by comminution in grinders or mills. All South African power stations use pf boilers, so coals have to be pulverised to an efficient burnable size, typically 75 µm. This specification therefore makes a mill an integral part of any power plant burning coal. Owing to their characteristics, coals are sometimes soft or hard to grind, which then lead to abrasion during comminution. Abrasion is known to be caused primarily by some inorganic matter and organic matter, ash content and moisture in coals.

Comminution is a process of reducing solid material into smaller fragments using a mill or grinding machine. A mill is a mechanical device built to grind, cut or shape solid materials into their powder form. Comminution therefore can simply be explained as a mechanical and physical breaking of material during milling or grinding into smaller fragments. During grinding, mill components, this including the grinding elements, suffer abrasive wear or erosion. Mills are therefore constructed from harder materials aimed at their durability and reduction in wear, especially where hard materials like minerals and coals are ground. However some materials are

harder than the mill materials and will reduce the mill longevity by abrasive wear. The mills therefore become cost ineffective in terms of maintenance and material replacement. Replacement of worn out material and power loss constitutes most of the cost in power plants (Spero *et al*, 1991; Scieszka, 1996). To understand the extent to which material wear occurs in mills during comminution, the abrasive character of coals has to be established.

Abrasion is a phenomenon that involves either erosion and/or material wear which results when a particle is trapped between the mill components and its walls during comminution (Hutchings, 2002). Abrasion is a tendency of a coal to wear away mill components (Falcon and Falcon, 1987). During comminution, especially where hard materials of strength greater than that of mill grinding components are ground, friction occurs. This friction cause abrasive wear (Khruschov, 1974; Sihna *et al*, 1982; Austin *et al*, 1984; Chenje and Radziszewski, 2004; Radziszewski *et al*, 2005). To study the abrasion of coals, an index termed abrasion index (AI) was established first by Yancey, Geer and Price in 1951 using YGP test rig. Currently AI is measured using different methods, which include the abrasion index tester pot using four iron blades as cutting elements (Spero, 1990). Mass loss of the blades used to grind is then divided by the charge mass. Mathematically this is given as:

$$AI = \frac{M_{Fe}}{charge\ mass} \quad (1)$$

There are two primary forms of abrasive wear that occur during milling, namely: two-body abrasive wear and three-body abrasive wear (Misra and Finnie, 1980; Hutchings, 2002). They are synonymously known as sliding and rolling abrasion respectively. For this study, an assumption is made that three-body abrasive wear will result when coals are ground in an abrasion index tester pot. This consideration was made due to the fact that: as coal particles are fed into a pot they are loose and become mobile, and these particles are partially trapped by the mill surface and its grinding zone in an enclosed system. There exists a wealth of information on two-body abrasive wear as oppose to three-body abrasive wear, but, Scieszka (1996), Misra and Finnie (1980), Rabinowicz *et al* (1961) and Toporov (1960) have studied three-body abrasive wear processes, some even going as far as designing equipment for studying it. A full study on three-body abrasive wear is found in the work by Misra and Finnie (1980).

Misra and Finnie (1981, 1983) showed that two-and three-body abrasive wear is not only concerned with hard material, as material of less hardness than the concerned metal blades can still cause material wear. Spero (1990) revealed that the effects of particles that are less hard than the cutting blades are inconsistent in comparison to harder minerals. Arguably it is known that the only way to proportion the effects of mineral hardness in coals is by combining all abrasive components of coals. These primarily will be the existing minerals, ash contents and organic components in coals. Also the physical properties of the coals must be included. In general abrasion can either be determined empirically or by grinder machines (Raask, 1985; Spero, 1990). It is established from literature that abrasion is dependent on some coal properties such as mineral matter (quartz and pyrite), moisture, ash content, bulk density, and grindability.

Abrasion is not the only physical property of coal that is of concern during comminution. Other physical properties such as coal strength, hardness, friability and grindability are of concern to cutting machines in the coal industry. Coal strength refers to the resistance of coal to grinding or crushing. Friability refers to the ease at which a coal can be compressed. Hardness refers resistance of coal to penetration, and grindability refers to the resistance of coal to grinding. Further definitions are given in Falcon and Falcon (1987). Grindability is of importance to this study, because this characteristic may enlighten the researcher on the breakage ability of a coal, and hence its hardness and ease of grinding. Grindability can also be used to establish the power consumed by a mill during comminution, making it possible to understand the abrasiveness and hardness of coals.

Abrasiveness, friability, hardness, strength and grindability of coals are all studied in order to understand their effect on mills and all mechanical equipment used in coal processing. These physical properties of coals reduce the life span of mechanical machines for cutting, grinding or crushing which results in cost effective operation and non-operation during replacement. If known, these characteristics will help with the planning of power plant maintenance. The harder the coal, the longer it takes to grind, the quicker the mill components are worn. The more friable a coal is, the easier it is to grind, the softer and looser it is. AI and Hardgrove Grindability Index

(HGI) are studied here so that wear in mills can be established. HGI is an index used to indicate the difficulty with which coals grind. It is a dimensionless quantity. An objective of this study is to determine if the (AI) and (HGI), empirical correlations, developed by Scieszka (1985), can be verified using experimental results;

$$A = f(G, B) \quad (2)$$

$$where: G\ (grindability) = f(M\ \rho\ m\ \Theta\ \acute{\eta}\ q) \quad (3)$$

$and\ B\ is\ the\ tribological\ properties\ of\ the\ grinding\ machine$

1.1. Motivation

The underlying principle behind this research was to establish the key characteristics of five South African run of mine (ROM) coals, from the Witbank coalfields, which lead to abrasion during grinding. The insight on abrasiveness of the ROM coals may help in reducing costs incurred during milling, by planning maintenance properly and helping with the identification or selection of materials for blade composition. Currently in South Africa there is no acceptable standard method for testing coals for abrasion. The technique referred to as YGP is most commonly used to test for abrasion. Over the years there have been some modifications to this method which have resulted in inconsistent and conflicting results produced by both mining houses and coal users (such as Eskom). To this end, this study serves as part of a larger project that will aim at devising a standard method acceptable for testing coals for abrasion in South Africa.

1.2. Aims and Objectives

The primary aim of this study was to investigate coal characteristics or components in coals that lead to abrasiveness during comminution. This research work specifically seeks to: (1) determine if the AI and Hardgrove Grindability Index (HGI) empirical correlations, developed by Scieszka (1985), can be verified using experimental results; (2) determine if excluded minerals and included minerals are equally abrasive; (3) establish the type of abrasive wear that occurred during coal grinding in an abrasion index tester pot. In addition, an investigation into how some

mechanical properties of coals influence power utilised by mills during comminution was undertaken. It has to be said right away that this investigation was carried out empirically. That is, mathematical models were used to calculate the energy drawn by an AI tester pot during grinding.

To execute this aim the following objectives had to be achieved: Coals were characterised using petrography, scanning electron microscope with energy dispersive X-ray (SEM-EDS), Powder X-ray diffraction (XRD), X-ray fluorescence (XRF) spectroscopy for organic and inorganic matter. Thermal gravimetric analysis (TGA) and oven moisture were used for proximate analysis and moisture analysis respectively. Abrasion index tester pot, Hardgrove machine, and sieve methods were used to determine the grinding properties of coal samples. Results were related to AI for each coal sample analysed. To satisfy the experimental relationship between AI and HGI following on the empirical correlations developed by Scieszka, regression analysis was used. To satisfy the effects of excluded and included minerals on abrasion, carbominerite (representation of included minerals) and excluded minerals determined petrographically were accessed. Topography of blades analysed using SEM-EDS was used to conclude the kind of abrasive wear that occurred during grinding (two body, three body).

The AI of a coal was measured using of an abrasion index mill tester following BS 1038:19 as given in Wells *et al* (2004) and Spero (1990). HGI was measured following a standard method, ASTM D-409.

1.3. Research Questions

From the aims and objectives stated above research questions were formulated. Such research questions included:

Which coal constituents have a greater effect on abrasiveness of ROM coals?

What effects do included and excluded mineral matter have on AI?

Will the experimental relationship between AI and HGI follow their mathematical relation given in Scieszka (1985)?

For this study a hypothesis was stated, which is: minerals included in the coal matrix are equally abrasive as excluded mineral matter on the four blades used as cutting elements in an abrasion index tester pot used to test coals for abrasion.

1.4. Scope of the report

The structure of this report is as follows: In Chapter 2 a literature review discusses aspects such as comminution, abrasion (what is abrasion, different kinds of abrasion wear, mill types and milling mechanisms), the use of SEM-EDS in establishing the kind of abrasion wear that occur during comminution, the use of petrography and XRD in establishing coal constituents causing abrasion, mill efficiency and powers are discussed in greatest of depth. In Chapter 3, experimental set up details sample preparation and experimental procedures. Chapter 4 discusses findings of this research, with Chapter 5 covering summary and conclusion for each set of results discussed. Following that, in Chapter 6 benefits, recommendations, and future work are given. This is followed by references. Finally the appendices are given.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

Coals are heterogeneous, naturally formed fossil fuels and are in abundance in South Africa. In South Africa, coals account for 92% of electricity that is generated by Eskom through their coal fired power stations. Coals are used by Sasol for the coal to liquid process plants (CTL), and certain coals are used as reductants and the fuel in the metallurgical industry. For power generation, coals need to be pulverised since coal fired power plant boilers are designed to combust a pulverised fuel (pf) that is sized at -75 micron. Size reduction is achieved through comminution using a mill. During size reduction, abrasion results due to friction. Abrasion is a tendency of material to wear away machinery; it is measured by material's abrasion index which is a weight loss suffered by blades used as cutting elements in an abrasion index tester pot after coals have been ground. In Chapter 1 different kinds of abrasive wear are outlined which shall be discussed in details in this chapter.

Abrasion index of coals are dependent on certain constituents of coal (for e.g. moisture). These constituents range from chemical, physical through to mechanical properties. In this study chemical and physical constituents of coals that influences abrasion index of coals are studied. To study chemical and physical properties of coals certain analytical techniques and techniques like Sieve method and Hardgrove machine were used respectively. These techniques are discussed in the following sub-sections of this chapter. Overall, this chapter discusses in detail the formation of coals; particularly the Witbank coals, comminution, different kinds of mills used in comminution, concepts of abrasion, grindability of coals, minerals and their effects on abrasion index of coals, analytical techniques used for characterising coals, and the mechanical properties of coal and power utilised by a grinder when it is grinding coals.

2.2. Coal formation

Coals were formed millions of years ago where marine like swamps and bogs had accumulated. Due to different weathers and conditions of burial, two ages of coals are known namely: Permian age and Carboniferous age (Falcon, 1986). These ages represent the coals of the Northern Hemisphere and Southern Hemisphere respectively. Coals of the Southern Hemisphere (South African coals included) are different from those that deposited in the Northern Hemisphere in that they are formed from different types of plants, climate conditions, pressures and time of burial (Falcon and Ham, 1988). Coals consist mainly of organic matter and inorganic matter, which are synonymously known as macerals and minerals respectively. In general coals are known to be heterogeneous, not only because they comprise of macerals and mineral, but also because they have other constituents such as moisture and macerals-minerals association (or microlithotypes).

South African coals have well been studied in the past, in terms of their composition, burning ability and potential for use. There is a wealth of information on South African coal deposits, particularly the Witbank coalfields (No-02 seam), which was first discussed by Snyman (1961, 1976) then Falcon (1981), both cited in Holland *et al* (1989). Falcon and Ham (1988) and Holland *et al* (1989) reveal that coals of this region are highly variable in quality, maturity and occurrence. They even vary from seam to seam or in-seam variation. Falcon (1989) listed factors that influence the differences seen with South African coal seam(s). These factors allude to macro and micro factors affecting coal seam quality and distribution.

South African coals rank from sub-bituminous to anthracite (Falcon and Ham, 1988; Falcon, 1989) and are generally rich in inertinite maceral and mineral matter. Bituminous coals of South Africa are found in the Mpumalanga (MP) region and anthracite coals are found in the kwa Zulu-Natal (KZN) region. South African bituminous coals are typically characterised by vitrinite reflectance that range from 0.6-0.8 %. Meaning that, South African coals are of medium to low rank. Rank refers to the maturity of coals. Literature stated that high contents of vitrinite in coals will correspond to low contents of inertinite, liptinite and mineral matters. Collectively, vitrinite, liptinite and inertinite constitute the primary macerals present in coals. However, in South Africa there is a fourth type of a maceral called semi-reactive inertinite maceral which is desirable for

effective combustion. Mineral matter refers to the grade of coals. For the purpose of this study mineral matter will also be referred to as minerals.

2.3. Coal comminution

The presences of organic constituents (or macerals) in coals have rendered coals suitable to be used for power generation (combustion process), for gasification and as a reductant in the metallurgical industry. Coals are the primary source of energy in South Africa and elsewhere; particularly where oil reservoirs have been depleted. Coals are reduced to pf size for combustion. For this stipulated size to be achieved, coals are crushed, milled or ground. Grinding, milling and crushing are encompassed within comminution. Comminution can be defined as a process in which solid materials are reduced in size using a mechanical device. Mechanical device refers to a mill, a grinder or any device that can be used for mineral or material processing or reduction.

There are many problems that are associated with coal comminution. Problems such as abrasive wear and erosion (Raask, 1985) are profound in size reduction, particularly where hard minerals present in coals are crushed before handling and use. Falcon and Falcon (1983) believes that minerals are potentially hazardous to mechanical designs used for material handling and processing. Minerals present in coals are named impurities and may be characterised of strength (moh's scale) greater than the strength of materials used for the construction of both mills and the grinding elements (e.g. blades). During comminution, especially where hard materials of strength greater than mill components are ground, friction occurs (Sihna *et al*, 1982; Khruschov, 1974; Austin *et al*, 1984; and others). It is by friction that abrasive wear result. Due to abrasive wear, comminution is a very cost ineffective process, both in operation and design.

2.4. Mills

A mill is a mechanical design used for size reduction of materials like coals and other minerals. Mills are chiefly used for coal processing and preparation. Mills encompassing roller crusher, ball mill, ring mill and others are typically used for the reduction of materials to sizes manageable and handleable for different engineering processes (for example combustion). In the combustion industry, mills are fitted to combustion units of power plants that burn pf coals. It is already established that most of the South African combustion units burn pf coals. A pulverised coal can be defined as a coal of size less than 75 µm. Owing to this specification; mills form a primary component of the combustion unit for all pf combustion power plants.

It is established that mills form the greater part of the pf power plants. To this end, there are many factors that need to be considered in relation to size reduction during operation. Factors such as abrasive wear, the nature of the mill, throughputs, efficiency and operating conditions, and the nature of coals being ground are taken to consideration. Of all the listed factors, the nature of the coals, and the mill throughput and efficiency are of most importance since they are inter-dependent. Mill efficiency and mill throughput can vary from coal to coal (Tavares and King, 1998). This appears to be true even when the mill is operated at same conditions, and coals are fed to the mill at constant feed rates (Eswaraiah *et al*, 2008). This means efficiency and throughput of every mill used to grind coals is dependent on the nature of coals being ground.

Mill efficiency and throughput are directly related to the breakage ability of coals (Scieszka, 1996; Tavares and King, 1998; Radziszewski *et al*, 2005; Al-Thyabat and Miles, 2006; Sahoo, 2006; Stamboliadis, 2007; Eswaraiah *et al*, 2008). Efficiency and throughput are not only important because of their relation to breakability and nature of coals, but also because they are relatable to the cost and maintenance of the grinders (Scieszka, 1996). The breakage of ground material is proportional to the power or energy consumed during comminution (Eswaraiah *et al*, 2008). The replacement of the worn mill grinding elements (blades) and power consumed during comminution constitutes the costs of grinding abrasive coals (Spero *et al*, 1991; Scieszka, 1996). Due to these factors a fully functional mill has to be designed from proper wear resistive materials (Hutchings, 2002). Whilst the mill components are very important, their design and construction is beyond the scope of this study and will not be considered.

2.4.1. Types of mills used in comminution

Mills operating at full scale power plant comprises of four primary important components. These are the coal drier, the transporter, the classifier and the grinding zone. For research purpose, especially where abrasiveness and grindability of coals are investigated, the grinding zone is simulated (Tichanek, 2008). Coal pulverisers operating at full scale plants are classed into four different kinds (Sligar, 1996; Australian Coal Association Research Program, 2008). They are classed as high speed mill, medium speed mill or vertical spindle mill, low speed mill and very low speed mill. There are different kinds of mills available in pf power plants which use different comminution mechanisms. The most commonly used mills are: hammer mill, ball-race mill, liner mill, impact crushers, jaw crusher, and vertical spindle mill (Spero *et al*, 1991). At the industrial scale all designs are motivated by the mill efficiency and throughputs, which are directly related to the cost and effective maintenance of mills at full scale plants, and in return motivate the selection of a mill used for ore processing (Peatfield, 2003).

2.5. Abrasion

Abrasion is a phenomenon that involves either erosion and/or material wear which occurs when a particle is trapped between the mill components and its walls during comminution. More precisely, abrasion is a tendency for a coal to wear away mill components (Falcon and Falcon, 1987), a physical property that is measured using the abrasion index tester pot reported as AI (mg/kg). From the given definition of abrasion, it is self explained that abrasion is a concept involved within comminution, friction and material wear. Abrasion always manifests itself during the grinding of materials, particularly when hard minerals are ground (Hutchings, 1992). It is understood that during grinding of hard minerals friction occurs due to the sliding of materials over the abrading surface. Consequently, due to friction, abrasion results (Austin *et al*, 1984).

There are two traditionally accepted classes of abrasive wear since the 1960's. The two abrasive wear classes are two-body abrasive wear and three-body abrasive wear (Hutchings, 2002). Gates (1998) defined two-body and three-body as a wear of a metal surface sliding against a rough, hard body (here particles are constrained from moving), and a wear that is caused by free

abrasive particles present as an interfacial element between a solid body and a counter body respectively. Generally, it is said in literature that, in grinding context three- body abrasive wear is more severe than two-body abrasive; hence the terms high stress abrasive wear and low stress abrasive wear denoting three-body and two body abrasive wear respectively

In any abrasive wear investigation, the distinction between these two kinds of abrasive wear must be made. The distinction helps by controlling abrasive wear in mills at full scale thereby also helping in the planning of the maintenance (Gates, 1998). Before a detailed background on abrasion is given, it is of interests to quote Gates' view on the classification system since it was incepted in 1960. Gates says: "Unfortunately, there has been, and remains a serious lack of uniformity in the approach to classification. This is a problem, since if publications reporting the results of tribological research use ambiguous terminology, it is difficult for others to make use of the information" (Pg. 139, paragraph 3). In this view, it was ascertained that since the 1960's accepted classification and reclassification efforts by Misra and Finnie in 1980, there is a confusion in literature which will remain unless if tribological researchers move away from these classifications and device new classification system. Gates (1998) in attempted to answering to this concern reclassified abrasive wear into mild, severe and extreme wear. This classification system appears to be based on the initial classification by Misra and Finnie (1980).

2.5.1. Types of abrasive wear

Literature reveals that two-body abrasive wear is greatly studied when comparing to the three-body abrasive wear (Misra and Finnie, 1980). The reason for this consideration is probably due to the known fact that: two-body abrasion is well observed with earth moving machine (mining equipment) or material removal process which are used intensively for everyday processing, while three-body abrasive wear occurs predominantly within the agriculture industries (Misra and Finnie, 1980). Despite this observation, a detailed study on three-body abrasive wear is given in Misra and Finnie (1980). Sciezska (1996) undertook a detailed three-body abrasive wear study using coals as ground material. It is defined that three-body abrasive wear will occur where materials are loose and free to roll, and therefore spend only part of their time actually cutting into a metal (Misra and Finnie, 1980, 1981; Spero *et al*, 1991; Gates, 1998). Illustrations of how

these wear occurs is given in Hutchings (2002). The summary which is illustrated in this study in the scanning electron microscope section.

Literature divided three-body abrasive wear into closed three-body abrasive wear and open three-body abrasive wear, no further classification of two-body abrasion is given. Closed three-body abrasive wear will arise when loose materials are confined between two rolling or sliding surface which are very close. This means abrading surfaces are radial close to each other. Toporov (1960) and Rabinowics *et al* (1961) have studied this kind of three-body wear extensively. They are also referenced by Misra and Finnie (1980) who perceives the two as the foremost people to study this type of wear. In this kind of wear, hard material will first attack the softer surface of the mill components thereby indenting it.

Close three-body abrasive wear is established to occur when solid material break into a bearing of the surfaces which are premeditated for adhesive wear, which then result in early and disastrous failure of sliding surface (Khruschov, 1974; Misra and Finnie, 1980). This wear is therefore contagious since the softer surface is attacked first thereby inducing wear on the entire surface. That is structural deformation if you will. Filters, seals and flushing can be used to constrain this wear from occurring (Misra and Finnie, 1980).

Open three-body abrasive wear will result when a particle is enclosed within two surfaces which are a distant apart. Unlike closed three-body abrasive wear, this kind of wear is hard to control, since it is an inherent feature of a process; it can only be controlled by proper choice of material used for handling and processing. It is predicted that for open three-body abrasive wear to occur there must exist a thick bed or abrading particles must be large such that the two abrading metal surface are so far part for the mechanical properties of one to influence the other. It is of importance to note that others view open or close three-body abrasive wear as two body abrasive wear (Gates, 1998). Even though such case exist, Misra and Finnie (1980) made a proposal that in open three-body abrasive wear there is no need to have a second counter-metal, thus in certain situations like impact crushers (where the is no supporting surface and forces are purely by inertia), and solid particle erosion can be regarded as three-body abrasion. Open three-body abrasive wear is further divided into gouging, high stress and low stress.

Gouging wear results when hard abrasive particles cut into material and impinge it. This type of open three-body abrasive wear is prominent with pulverisers that use impact mechanism for grinding (Misra and Finnie, 1980; Scieszka and Dutkiewics, 1991). High stress open three-body abrasive wear manifests itself predominantly where ball mills are used for grinding hard abrasive particles (Misra and Finnie, 1980; Scieszka, 1987). Low stress open three-body abrasive wear results when ground particles remain intact during the wear process (Spero *et al*, 1991; Scieszka, 1996). Simply, a wear that occurs without material being fractured is termed low stress open three-body abrasive wear (Misra and Finnie, 1980; Scieszka, 1996). Gates (1998) informs that the latter classification is characterised with less ambiguity than all classification systems currently available in literature.

Another well known type of abrasive wear is erosion. This type of wear is induced by hard particles striking the mill surface, which may be carried through either by gas or flowing liquid (Hutchings, 2002).

2.5.2. Coal abrasion determination

The abrasion of coals is studied using abrasion index tester pot following a method named YGP which has long been proposed by Yancey, Geer and Price in 1951. Abrasiveness nature of coals is determined by calculating AI of ground coals. Abrasion index is a function of the total mass lost by the iron blades divided by the load mass of coals (Scieszka, 1985, 1996; Spero, 1990; Spero *et al*, 1991)-see Equation 1, Chapter 1. The method is now in standard form and is described in details by Spero *et al* (1991). BS 1016:19 is one of the standardised AI methods. It appears from Sligar (1996) that of all the experimental methods used for determining AI of coals, YGP-abrasion tester is acceptable in South Africa, Australia, India and the United Kingdom. On the industrial scale the marked ball test is acceptable. The use of the marked ball and the YGP tester might be responsible for the inconsistent and incorrect results produced by both the mining houses and coal users such as Eskom (this is alluded to in Chapter 1, Section 1.1).

Raask (1985) has shown how empirical formula can be used to determining abrasion index of coals, but recent developments which involve the use of mills and grinders for determining the AI of coals have sort of saw the empirical formula being discontinued. Since the inception of mills for testing coals for AI, different kinds of mills have been used (Austin *et al*, 1984; Scieszka, 1985, 1987, 1996; Spero 1990; Spero *et al*, 1991; Sligar, 1996). All the techniques used for studying abrasive wear are tabulated in Spero *et al* (1980) and Sligar (1996). Hutchings (2002) has revealed that the first mill to be used for studying AI of rocks is Grindstone in 1752.

The techniques used for studying AI of coals include YPG abrasion tester; which is traditional, CE Raymond abrasiveness test, and the most recent mill called Tribo-tester, which was developed and commissioned by Scieszka. At a laboratory scale the most predominantly used mills are Abrasion tester and Babcock mill. These mills are used with different standards such as BS 1038:19, BS 1016:111 (1998), and the one YGP method (Wells *et al*, 2004). It is important to note that different mills will respond different to same materials, and do not use same mechanisms for grinding. The most predominantly utilised mechanism by mills for size reduction includes attrition, impact and crushing mechanism.

Not only do abrasion tester utilise different mechanism for size reduction, they also use different cutting or grinding elements (Spero *et al*, 1991). For instance, some mills use rods as grinding elements and use impact mechanism for crushing, while other mills use steel balls for grinding and the attrition mechanism for size reduction. The grinder that was used for this research, to test coals for their abrasiveness, used four iron blades as cutting elements, utilising attrition mechanism for size reduction. Ball race mill, which are mostly used in comminution, use balls for crushing and crushing and attrition mechanism for size reduction (Scieszka, 1987). YGP mill, roll mill, hammer mill all uses attrition mechanism. Jaw crusher uses compression, shear and impact forces with less attrition. Babcock mill and abrasion tester mills use attrition, compression, and shear force mechanisms for size reduction.

Figure 1 illustrates the YGP abrasion index tester mill used in testing coals for abrasion index. The picture illustrates the impact forces that act on the coal particle during grinding. Two most predominant forces are centrifugal force and the radial force. All these forces lead to particle reduction. The small n shown in the picture represents the null vector, which in most cases is a

unit vector such that the cosine force exists. The radius shown in the picture is important because it is normally used to calculate the force and mass moment of inertia which is used to calculate the energy of the grinding mill. The radius is called gyration radius. The square like top-open chamber is a coal container used to enclose coal particles during grinding.

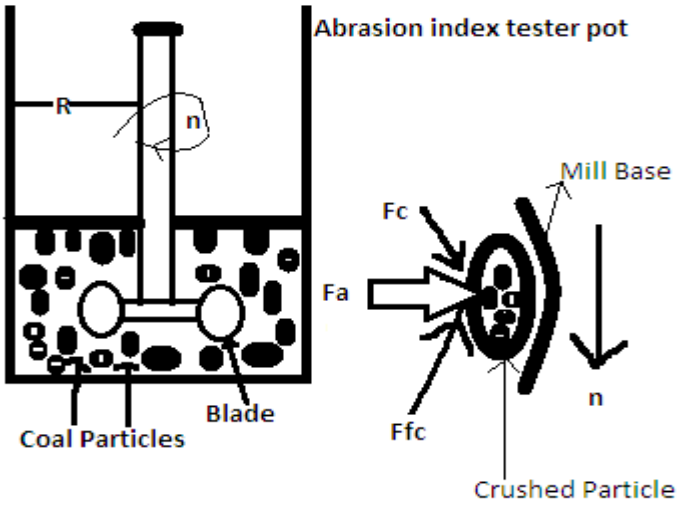


Figure 1: YGP abrasion index tester pot (Spero *et al,* 1991)

In the YGP method, coal of a certain particle size weighing 2 kg is introduced to the grinder having four blades as cutting elements. The charge is ground by rotating a mill at 12000 revolutions (rev) at 1470 rpm. At the end of the set 12000 rev, ground coals are removed and contained. The blades are weighed on a calibrated balance, from which the difference is divided by feed mass. The results are then taken as an indication of the AI of the coals.

In general, abrasiveness of coals is known to be influenced by different coal constituents (Spero, 1990; Spero *et al*, 1991), which can be divided into chemical, physical and mechanical properties. Chemical property that influences abrasiveness is moisture; ash content does not influence the AI of coals Terchick *et al* (1963). Physical properties of coals that influence abrasion are minerals (excluded minerals, quartz, pyrite and clays), microlithotypes (carbominerite) and macerals (inertinite rich). Abrasion intensity and abrasion factor are two mechanical properties from which abrasion is dependable (Spero, 1990). Hardness and

grindability of coals may influence abrasion (Scieszka, 1985; Spero *et al*, 1991; Hutchings, 2002). In any grinder or mill it is understood that abrasion is high at the beginning and becomes low at the end, this is controlled by particle size distribution (PSD). These aspects are discussed next in this chapter.

2.6. Particle size distribution

Particle size distribution (PSD) refers to different size class of ground material. Particle size distribution is determined traditionally using sieving methods. Normally meshes of different sizes are stacked from which material will be passed. Material sieved will be classed according to their sizes. The method seeks to reveal the physical and chemical nature of a powder material. The method is also capable of revealing how particles of the same composition can be distributed during sieving after grinding. Mazumdar and Irdi (1988) showed how the method is applicable to determining the dissemination of pyrite mineral in coals.

The most popularly used method for PSD analysis is Sieve analysis method. Alternatively, mathematical techniques involving this analysis exist, which are used to compare to the sieve analysis methodology. Today Malvern techniques are preferred for PSD analysis. There are other theoretically proved methods for describing the distribution function of ground material. The methods are log-normal distribution, proved by Kolmogorov (1941) and the Weibull distribution or Rosin Rammler distribution (1951). These two described methods are used to assess (theoretically), whether the Sieve analysis method works by describing the manner in which material particles distribute after grinding.

The effects of coal particle size on abrasion have been studied. Yancey, Geer and Price cited in Spero (1990) concluded that the greatest of abrasion suffered by wearing blades used in the abrasion test was caused by coarse particles. Further Spero (1990) reveals that any coal that will reduce faster to fine product will exhibit the least abrasiveness, while the one that is tough cannot rapidly be pulverised, it will therefore exhibit high abrasion over a certain period of time. Abrasive wear is known to be dependable on the moisture in coals, on the shape and size distribution and certain concentration of the harder minerals present in coals (pyrite and quartz). Angular minerals are known to be far more abrasive than round particles. Particle size analyses

have led to an understanding that quartz and pyrite in coals are abrasive until approximately 100 microns. The study on PSD's has shown that above this threshold, AI remains relatively independent of the size of quartz and pyrite present in coals. This phenomenon is abrasion size effects. This phenomenon was found to be prominent with round particles as oppose to angular particles.

2.7. Minerals in coals

Mineral matter (MM) in raw coal is a very important aspect of coal technology, especially in processing and utilisation. In coal studies, mineral matter refers to the inorganic materials which are free and are disseminated within the coals matrixes and macerals (microlithotype) (Gary *et al*, 1972). Similar definitions are given in studies by Harvey and Ruch (1986), and Creelman and Ward (1996). Their definitions embrace the following three different fundamentals constituents of mineral occurrence in coals; (1) dissolved salts and other inorganic substance in the coal's pore water; (2) inorganic elements incorporated within the organic compounds of the coal macerals, and discrete inorganic particles; (3) both crystalline and non-crystalline materials of true mineral components.

The difference between these three constituents is that; the first two are characterised as apparent in the mineral matter of low rank coals. They are also described as non-mineral in organics which contribute greatly to the formation of ash in the deposit of low rank coals (Kiss and King, 1977, 1979; Given and Spackman, 1978; Benson and Holm, 1985). Discrete inorganic particles occur in both low rank and high rank coals. Dissolved salts and inorganic elements occur in small amounts in high rank coals. Their occurrence in small quantity is due to their removal by moisture and chemical structure changes of organic matter (Ward, 2002).

South African coals are rich in minerals which occur in different forms and distribution. These minerals can be grouped as carbonates, pyrites, clays and quartz (Falcon and Ham, 1988; Falcon, 1989). Falcon (1989) characterised these minerals to occur as finely distributed (1-10mm), with evenly distributed aggregates of clay minerals. These minerals appeared to occur in "Whisps and lenses, and as cavity in fills within all macerals"-Pg 703, paragraph 3. This could mean minerals within the investigated Witbank coalfield occur primarily as included minerals. Collectively,

included minerals and excluded minerals represent the forms in which minerals disseminate in the coal carbon matrix thereby constituting two classes. The classification is purely based on the mineral-organic association. Association of minerals and macerals refers to microlithotypes.

Excluded minerals are defined as discrete minerals or those minerals that are liberated from the carbon matrix during grinding, while included minerals are said to be those minerals that associated with organic matter. These definitions are based on computer controlled scanning electron microscope (CCSEM) which paved its way into coal particle classification of pulverised coals. South African coal seams comprise mainly of clay, quartz and pyrite minerals (Falcon and Falcon, 1983). It is established from literature survey that coals found in the Witbank area are generally rich in mineral matter content, which is reported to be between 20 and 25%.

Abrasion and erosion are amongst many problems that can be related to coal comminution. Abrasive wear is attributed by Raask (1985), Sciezska (1985, 1996), Spero (1990), Hutchings (2002), Wigley and Williams (2005), and Wells *et al* (2004, 2005) to the minerals present in the coals, especially those that are harder than steel. This is supported by Wigley and Williams (2005) who say coals that are free of ash (or coals that have little amounts of minerals) would not cause significant abrasion or erosion in coal plants, however, the most mineral impurities present in coals chiefly cause the greatest of wear in the full scale power plants. Other authors attribute abrasion wear to the ash content of coals and moisture (Meintjes, 1965), though Terchick *et al* (1963) contend against ash content as a contributor to coal's abrasiveness. Ash content in raw coals may be taken as the residue of self-heated or in situ oxidised minerals.

During grinding or milling inorganic minerals can be liberated from the coal's organic matrix. Thus, excluded mineral and included mineral. Minerals such as quartz and pyrite are known to be very abrasive. Quartz in coals occur as moderately large particles of free mineral matter, whereas pyrite occur as finely dispersed grains in coals and the clay sediments (Falcon and Falcon, 1983; Wigley and Williams, 2005). It is well established that quartz are more abrasive than pyrite on volume % (Raask, 1985). This may be attributable to the fact that quartz, which are hard, when milled will shatter thereby producing sharp-edged fragments. The observation that quartz are more abrasive than pyrite was made with UK coals; this observation has not been

reported on world trade coals (Wells *et al*, 2004). However, Wells and co-workers found that angular quartz and pyrite on volume % are equally abrasive.

Other hard minerals capable of inducing abrasive wear are orthoclase, kyanite, topaz and alumina. This list of minerals may occur in coals in small amounts or may generally be present in trace quantities; this might be the reason why they sometimes have minimal effects on the overall reported AI of coals (Wells *et al*, 2004; Wigley and Williams, 2005). Other mineral groupings such as the clays, carbonates, sulphates and phosphate are relatively soft and do not cause any significant abrasive wear. In general, excluded minerals are most abrasive when comparing to included minerals, but it is highlighted elsewhere in literature that, a mineral associated with organic matrix of coal can be abrasive if only little of it is protruding.

2.8. Grindability

Grindability of coal is defined as the propensity for coals to grind (Callcott, 1956). The grindability of coals was first discussed in the 1930's by Hardgrove after the realisation that the performance of grinding machinery or pulverisers is dependent on the type of coal being ground (Tiryaki, 2005). The grindability of coal is determined experimentally using a grinding machine, following particular standards, and it is reported as a Hardgrove Grindability Index (HGI). HGI is indicative of the hardness of coals to grinding (Bagherieh *et al*, 2008). A soft coal is indicated by the high HGI value (typically above +60), whilst the hard coal is shown by the low HGI values (below 55) (Snyman, 1989; Tichanek, 2008).

HGI is important for boiler designs (Tichanek, 2008) and commercial use; where coals on trade are classed according to their hardness realising their HGI values (Tichanek, 2008; Chelgani *et al*, 2008; ACARP, 2008). HGI values are used by mining engineers to categorise coals according to their resistance to cutting and grinding (Tiryaki, 2005). HGI is an important index as it can be used to indicate the effectiveness of the mill to grinding different coals, hence their capacity at full scale power plants (Warren Spring Laboratory, 1962; Chelgani *et al*, 2008; Tichanek, 2008). Bond work index, which is related to HGI, is particularly used for this purpose. There are empirical equations which relate these two indices. The Bond work index is denoted by W_i is

defined as the energy required to reduce material of finite size to 80% passing a 100 micron mesh (Warren Spring Laboratory, 1962; Levin, 1989; Tichanek, 2008).

The advantages of determining the grinding nature of coals lies purely on the fact that, if the grinding nature of coals is known then a proper mill can be selected for comminution. Also, HGI is indicative of which coals are suitable to be utilised for power generation. HGI and W_i (Together) are used to assess the rate of comminution (Scieszka, 1996). The power needed to achieve the specific particle size can be determined if the HGI is known, thereby optimising or simulating the full scale plants (Terchick *et al*, 1963). This emanates from the fact that a revolution of a laboratory scale mill is equivalent to a certain specific energy consumed by a plant mill into pulverising a size feed material (Levin, 1989; Scieszka, 1996). The disadvantage of not knowing the grinding nature of coals will lead to poor performance of mills and poor management put in place which will render most money put forth into maintaining the mills.

In testing for this coal physical property, standards such as the American Society for Testing and Materials (ASTM) D-409 (1991), BS 1060 part 20 (1987), and ISO 5074 (1994) are used (Bagherieh *et al*, 2008). A grinding machine as shown by Figure 2 is typically used for testing coals for their HGI. This machine utilises impact mechanism for size reduction and uses eight balls as cutting elements, and is equipped with a mesh sized to 75 µm from which ground material will pass. Experimentally, HGI of coals is measured by determining 80% of material passing the target sieve.

In literature, USBM ball mill and a normal Grindability machine are the predominantly used mills to determine HGI of coals. In addition to the standard listed above, ASTM D409-51 and ASTM D409-71 are also recognised standards used to measure HGI for coals. The difference between the two ASTMs is that one measures the weight (g) of material passing a target sieve (normally 75 µm) and the other measures the volume (cm^3) of ground material. The former method is perceived to be unstable since the accuracy depends on the consistence and efficiency at which the pulverised material will be sieved. Even though this is a case, this method is widely used in literature, with ASTM D409-71 being the least known and used. In the past the grindability nature of the coals was determined empirically using the formula: $HGI = 6.93W +$

13 (Callcott, 1956; van Vuuren, 1978; Raask, 1985). Where *W* is the weight of material passing the target sieve. HGI can be predicted using chemical components of coals (de Kock and Franzidis, 1973).

In 1978 a survey was undertook in South Africa aiming at understanding the grinding nature of most coal collieries, this was motivated by both coal producers and consumers (van Vuuren, 1978). The survey by van Vuuren (1978) revealed many coal constituents that affect the grinding nature of South African coals. It emanates from the survey that the ash content, volatile matter and moisture content have a great influence on the HGI of coals. Low ash and high volatile matter coals appear to have low HGI, thus indicating that the coal is hard. It is articulated in the survey that most coals from the Witbank Coalfield are fairly hard to grind, with the HGI ranging from 42 to 52. Free State coals were found to be the softest because they had an index of 61 and appears to be weathered or heat effected (or abnormal conditions). Weathering of coals can alter their organic and inorganic constituents (minerals), and can also change their chemical and physical properties.

Falcon and Falcon (1987) reported the HGI of coals in Natal, Transvaal and Orange Free State to range between 31- 83, 40- 66 and 63-84 respectively. Reported results are attributed to the fact that these coals are of high ash, low volatile matters and very moist. Falcon and Falcon (1987) found that the inherent moisture contents of coals appear to affect grindability of low rank coal, but did not influence the HGI of high rank coals. It has to be emphasised that this behaviour is noble only with Southern African coals. These indicate that moisture could be one ambiguous constituent of coals to be used to establishing the grind nature of coals. The three discussed constituents of coals are what form the proximate analyses of coals.

Proximate results have been used to produce linear relationships with HGI using computer developed programs like non-linear multivariable regression and generalised regression neutral network. Petrographic results also form the primary constituents of coals known to influence HGI. Following the work of Li *et al* (2005), Baghereih (2008) developed artificial neutron network which incorporates petrographic parameters to predict HGI of coals. Minerals are observed to influence HGI of coals. Note that a separate section on petrography is given; it is

brought here only to elaborate how far research goes into trying to correlate many coal constituents to their grinding nature.

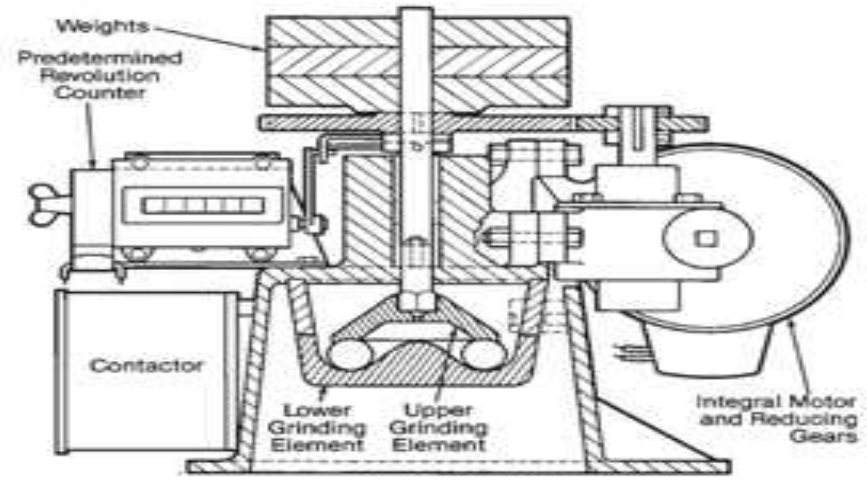


Figure 2: Grindability tester machine (ACARP, 2008)

Figure 2 represent the grindability tester machine used to determine HGI values for coals. The equipment comprises primarily of two main components: the lower stationary part and the upper rotating part. The lower stationary part consists of a tank with horizontal grinder track on which steel balls of size 25, 40±0, 13 mm move during size reduction. The upper rotating part allows movement of the grinding bodies (Tichanek, 2008). Lump coals sized to 4.75 mm are fed into the grinding zones where it will be reduced. The revolutions are set following ASTM. Normally material passing the 200 mesh (75 micron) sieve is weighed out, the weight which confirms the grinding nature of a tested coal (Tichanek, 2008). The recorded mass is converted into HGI value using calibration charts (ACARP, 2008).

2.8.1. Grindability and abrasion

HGI and AI of coals are closely related. Their relationship was elucidated first by Scieszka (1985), who gave their mathematical relationship, see equations 2 and 3. Mathematical relationship that suggested that: HGI is a sub-group of AI. This simply means the two physical properties of coals can exist in close proximities. It was shown by correlations using a series of different coals that these coal properties exhibit a quadratic relationship when correlated

(Terchick *et al*, 1963), but, if one looked closely it was obvious that coal of the same origin gave an independent relationship. Briefly, coals being soft (highest HGI) does not mean they are abrasive, and conversely hard coals are not readily abrasive.

2.9. Coal analysis

Coals have a very complex structure which is attributed to the presence of both organic and inorganic constituents. It is difficult to fully characterise coals due its complex structure and the dissemination of mineral matters within coal carbon structure. This difficulty has led to different analytical techniques being developed and designed in order to establish coal's potentials for utilisation. The designs of coal characterising analytical techniques came about particularly to answer problems that arise with coal processing and utilisation. All the problems that arose due to coal utilisation and processing were discussed initially by Raask (1985) and can be found elsewhere in literature (for instance Wigley and Williams, 2005).These problems include abrasive wear, which is investigated in this study.

Different analytical tools exist aiming at answering questions such as: which components of coals lead to abrasive wear; which coals are harder hence abrasive to mechanical designs such as mills for coal grinding; which minerals are present in coals and how minerals are disseminated and associated with organic components of coals. These questions include the forms and nature of the minerals found both inside and outside the coal matrixes. Huggins (2002) and Ural (2007) divided these analytical tools, particularly those used for characterising minerals in coals, into three different groups: viz; (1) Methods that measure elemental concentrations present in the coal as ashes (e.g., XRF); (2) Methods that determine mineralogical components present in coals (e.g., XRD); and (3) Methods that determine the mode of occurrence of elements present in a coals (e.g., optical and electron microscopes).

It is stated that minerals in coals occur as both included and excluded minerals. To this, advanced techniques that are able to characterise coal minerals as portions of either class are desirable. Several techniques can identify these coal constituents, which range from qualitative analyses combined with normative analysis, through semi-quantitative to quantitative analyses. In fact analytical techniques such as petrography and other megascopic and microscopic methods like

scanning electron microscopy (SEM), X-ray diffraction (XRD) analysis, and normative methods have been used before for the qualification, quantification, origin and nature of mineral matter in coals (Taylor, 1991; Ward, 1991, 1992; Creelman and Ward, 1996; Ward and Taylor, 1996; Ward *et al*, 1999). The way in which these analytical techniques are used for the determination and enhancement of mineralogy information are discussed below, which includes their limitations. Identification of minerals in coals is purely based on the fact that they pose a threat to all coal processing and utilising machinery or designs, which eventually becomes financially constraining. Therefore their understanding may be necessary for improving predictions of abrasive wear.

2.9.1. Petrography

Petrography is the science that deals with the systematic characterisation and classification of coal based on petrologic data (van Krevelen and Schuyer, 1957). The microscopic organic and inorganic constituents present in coals and degree of rank (metamorphosis) to which they have been subjected during their time of burial are considered (Falcon and Falcon, 1983, 1987; Falcon and Ham, 1988). The petrographic microscope is a very important tool in the coal industry, and it remains indispensable in obtaining information that correlates coal constituents and its technological response prior to coal utilisation process (Hessley *et al*, 1986; Falcon and Falcon, 1983). The primary limitations towards petrographic microscopes are their magnification and the fact that the microscope is time consuming since it uses point counting system for quantification of minerals (Mukherjee *et al*, 1994).

Early use of petrography in coal analyses were based on transmitted light following on the work pioneered by Thiessen and White (1913) cited in Falcon and Snyman (1986). In the same year, 1913, scientists in Germany had studied coal under petrography microscope using reflected light on the polished blocks. The latter method of analysis allowed the blocks to be studied with oil immersion objectives, the introduction which brought a great improvement in the resolution and optical quality of the analysed blocks. Reflectance of vitrinite in coals led to the understanding of the rank or maturity of coals. Rank is defined as the level which a coal has reached during coalification process. Vitrinite, together with liptinite and inertinite, are macerals component of

coals. Petrographic analyses in general have led to the understanding that coals comprise primarily of organic (macerals) and inorganic (minerals) components.

Reflected light microscopic analysis is the most widely used method of coal microscopic analysis. Typically, coal samples are crushed to at least -1 mm particle size, mixed with epoxy resin to make a block, which then gets to be ground and polished such that the surface for maceral and mineral analysis is free from relief, pits and scratches. Under reflected light the polished block is analysed. Conventional microscopic analysis on the block is carried out in the reflected light at a total magnification of 250 and 500. Maceral analyses are carried out under oil-immersion using less or more than 50x objectives and an automatic point counter at traverse spacing of 0.4 mm and intervals between the traverses of 0.5 mm. Maceral analyses can be done either individually or by groups, which are optimised at 500 point counts. Three macerals groups typically analysed for are: vitrinite, liptinite, and inertinite (conventional). In South Africa semi-reactive inertinite is an additional category (Falcon and Snyman, 1986).

Petrographic analyses enlighten the researcher about the rank of coals, macerals, microlithotype composition and minerals (both included and excluded), as well as the shape of minerals within the coal structure. Recently it has become possible, because of petrography advances, to study the abnormal conditions of coals (CAC) or the heat affected nature of coals. It can therefore be told that petrography will determine which coal constituents are most likely to cause wear. Several publications reported the correlations of coal petrology to its grinding properties (Hower, 1998) and coal's abrasiveness (Falcon and Falcon, 1987). According to Falcon and Ham (1988), South African inertinite-rich coals are abrasive due to the dense character of the inertinite maceral. Microlithotype groups dominated by this maceral are characterised as abrasive, as are carbominerite microlithotypes.

Microlithotypes are analysed following the same procedure as macerals group analyses. The distinction is the use of the 20 point graticule rather than a cross hair used in the ocular of the microscope. Three main groups of microlithotypes are known, namely: monomaceral, bimaceral and trimaceral. Carbominerite and carbopyrite are types of microlithotypes that are present in South African coals. The distinction between carbominerite and carbopyrite is made by

observing the intersection at which a maceral coinciding with a mineral(s) (Falcon and Snyman, 1986).

It was established in Section 2.7 that certain minerals do impact on the abrasion of coals during grinding. Minerals in coal petrology are referred to as inorganic matter and they are indicative of the grade of coals. Similarly macerals and microlithotypes do have an impact on the strength, breakage and fracturing ability and abrasion of coals. Coal strength refers to resistance of a coal to crushing. Falcon and Snyman (1986) revealed that vitrinite is brittle, and liptinite is tough and has high tensile strength, which then means liptinite can make coals resistive to grinding. Inertinite macerals, except for fusinite (inertinite group maceral), can comprise of thick layers which then results in high strength of coal bands in which it occurs. Fusinite is friable.

Falcon and Falcon (1987) undertook a detailed study relating the friability, hardness and abrasiveness indices of Southern African coals to their petrographic components. From the study it was observed that coals originating from the Free State (FS) have the greatest strength than the coals from KZN. This emanated from the conclusion that, apart from these coals having been oxidised (FS coals), they consist of bands that are rich in inertinite-durain, many with relatively high quartz contents. The study further concluded that an increase in inertinite will lead to high AI, and that an increase in quartz-rich bands and the association of quartz minerals and inertinite macerals result in tough coal of strength that can result in an abrasive coal. Abrasion is also related to associations of microlithotypes. It is established that carbominerite, bands of mineral-rich microlithotypes which is organic matter with 20% minerals in vol %, will render any coal abrasive.

2.9.2. X-ray Fluorescence

X ray fluorescence (XRF) is the method used to measure the elemental and chemical components of materials. It is a non-destructive method used to measure elemental or chemical analysis of minerals present in coals. It uses two fundamental processes; absorption or scattering of x-rays. When X-rays are absorbed by material bombarded with X-rays, the process is called photoelectric effect, and when X-rays are emitted by material the process is called X-ray Fluorescence. In turn a spectrum is produced with multiple peaks showing the material composition at different positions. Figure 4 illustrates the spectrum produced during XRF analyses. Figure 3 illustrates the trajectory path for the generation of the spectrum during XRF analyses.

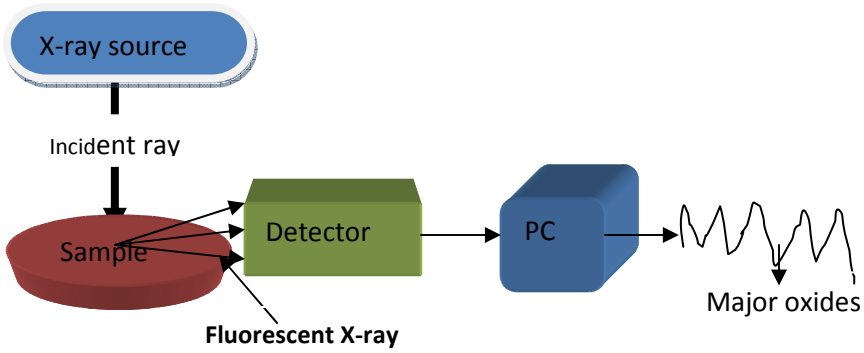


Figure 3: Basic principle of X-ray Fluorescence

Figure 3 illustrates the basic principle of X-ray Fluorescence. An incident beam is the energy from the X-ray source that excites the sample. The radiation source can either be a radioisotope or X-ray tubes. The interaction of incident light and matter lead to diffraction. The diffracted light due to dense material is referred to as fluorescence X-ray. Fluorescence X-rays are directly sent to the detector, which can be a solid state detector, where they are acquired then sent to the signal processing computer, which will then produce a spectrum that will indicate different major elements present in the coal sample.

Materials analysed using XRF are in powder form or solid material. When analysed, the sample has to be pelletised. The analyses stage requires that an X-ray transparent supporting media be

used. This can be material such as polyethylene. The acquired spectrum, as shown by Figure 4, illustrate peaks, each making it possible to understand material from which the analysed sample was made or composite. These peaks are of different energies. Their energies are used to identify the elements in the sample. This is essential qualitative analysis. The peak intensities can be used to suggest the concentration of different materials in samples. Major elements found to be present in a sample are reported in weight percent. Note that the spectrum will only show the major elements in the analysed sample, but, when reported the same elements are given as oxides. For instance silicon data obtained by XRF techniques is reported as silica (SiO_2), also other major elements in coals like iron (Fe_3O_4, Fe_2O_3, FeO) are reported the same.

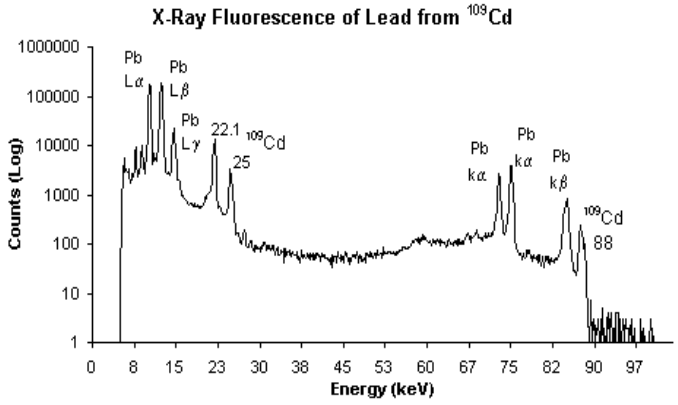


Figure 4: A typical X-ray Fluorescence spectrum (www.google.coza/XRF)

Figure 4 is a typical XRF spectrum. The spectrum shows the major chemical elements composing of the analysed material. The spectrum shown by Figure 4 is for lead (Pb) which was radiated using cadmium (Cd).

Points to note:

a) K, L, M or N are the characterising x-ray source which designate their sources;

b) Alpha (α), Beta (β) and gamma (γ) mark the x-rays that originated from the electrons that transmitted from the higher shells; and

c) Further designation is that of the orbital's such as 1a, 2a, 1b, 2b etc, which denotes the electron transition from a lower energy level to the same energy state.

In coal research, XRF is used for ash analysis. This ash is derived from high or low ashing temperatures. In coal research low temperature oxygen plasma ash analysis are used. This is such that mineral preservation occurs, as most minerals can be converted at high temperatures. Minerals present in coals can be converted when coals are naturally oxidised. Ural (2007) stated that XRF can be used to study minerals in coals before and after they are ashed, even though the ash is known to be slightly different from their minerals. This can be solidified by making an observation that during ashing, especially at high temperatures, minerals like clays dehydroxylated, with carbonates thereby losing their carbon dioxide (CO_2).

In general XRF is a non destructive technique. Their design envisaged for the analyses of lighter elements, but due to different instrumentation designs and yields of low X-rays by most elements, only heavy elements are detectable. The determination of such lighter elements is possible, but XRF must have background corrections and very comprehensive inter-elemental corrections. XRF has been used in conjunction with XRD technique to quantify minerals in coals, which eventually means it forms part of the broader scale of quantification techniques. This is done by taking LTA results and correlating them with quantitative techniques, there are also formula used for establishing minerals in coals following from XRF analyses. Ash in coals is one quantity that is portrait to induce abrasiveness in coals (Mentjies, 1965), but Terchick and co worker (1963) have argued that not so much ash but the types of minerals forming the ash can induce abrasiveness in coals.

2.9.3. X-ray diffraction

X-rays are moderately short-wavelength, high-energy beams of electromagnetic radiation; they also called photons. Single crystal X-ray diffraction is probably the oldest method of X-ray crystallography. X-ray crystallography is a method that allows the determination of different atoms and their arrangements in materials of different phases (Gupta, 2007; van Alphen, 2007). The materials analysed should be of non-amorphous phase or in crystal form for effective analysis. For the atoms in a crystal material to be detected by X-ray techniques, a beam of particular wavelength is directed onto a solid material or powder which will then be scattered in different directions at an angle 2θ following on Bragg's law. The scattering is thus elastic. From the scattered X-rays of same wavelengths as the incident X-rays, different electron densities

(resolved peaks) will be generated. These electron densities are generally used to generate the mean position of every atom in the sample under investigation. Information such as disorder and chemical bonding of generated electron density will be produced. XRD is overall a non-destructive, rapid technique with good reproducibility when it comes to mineral identification in a coal sample (Lu *et al*, 2001).

The use of the XRD for determining the minerals present in coals is simple because the minerals in coals have a defined crystal structure that makes it possible for their determination (Schoening, 1983; Creelman and Ward, 1996; Ward *et* al, 1999; Lu *et* al, 2001; Ward *et al*, 2001; Ward, 2002; van Alphen, 2007; Matjie and van Alphen, 2008; Vassilev and Vassileva, 2009). The use of XRD in coal, especially for mineralogy dates way back. Mahadevan in early the 1900 and about 1940's realised the use of XRD to study coals (Chandy, 1969). Riley (1943) and Blayden *et al* (1943) are amongst the first people to use XRD in studying minerals in coals (Chandy, 1969). Ward (2002) confirmed that XRD is the first tool to definitely confirm the crystalline phase matter in coals by in identifying particular minerals.

A number of different methods using XRD as a qualitative tool are given broadly in literature (Ward, 2002). Though XRD was long established as a definite tool in mineral identification, it is profound that when it comes to the quantification of the minerals in coals, this tool has its own shortcomings (Ruan and Ward, 2002). Its limitations include the preferred orientations by the minerals in a mount sample, mineral crystallinity, grain size of the different minerals, as well as the potential of absorbing the X-rays when mount in a sample (Ward *et* al, 1999; Ward *et al*, 2001; Ward 2002). Nevertheless several techniques today exist aiming at the quantification of minerals in coals. Some of the techniques are based on the bulk-sample XRD analyses, whilst others are based on the orientation of the cumulative studies only concerned with the evaluation of clay minerals in the sample (Ruan and Ward, 2002). In fact low-temperature oxygen-plasma ashing is used as a mineral semi-qualitative technique. It was used by different researchers to cross check the extent to which it can identify minerals qualitatively in coals, this was done by spiking LTA samples with a mineral of a known mass (Ward *et* al, 2001; Ward, 2002). The earliest methods used into the determination of mineral matter are Parr of 1928 and the KCM formula of 1936 (ward, 2002).

The use of Rietveld method proposed in 1969 brought a breakthrough in mineral quantification of minerals present in coals. It is known that, in 1969 Rietveld developed a formula capable of giving the intensity of a single mineral at any point in the diffraction pattern. The Rietveld method is used to quantify the portions of individual minerals in powdered coal samples (Ruan and Ward, 2002). Rietveld method has been used by different authors, such as Bish and Howard (1988), Hill and Howard (1987) (cited in Ruan and Ward, 2002) for the quantification of minerals in coals. The shortcoming of the method is outlined by Ward (2002), who contend that even though Rietveld method is good, the intensity of the diffractogram peaks are less informative about the mineral quantification than a full profile of an XRD pattern. SIROQUANT is another method developed for use as part of mineral quantification using XRD. This method is described by Taylor (1991). SIROQUANT is known to allow for the quantification of close to 25 different minerals in a mixture form a conventional XRD pattern using Rietveld method (Ruan and Ward, 2002).

Rietveld method generates an XRD profile of each mineral from its known crystal structure by method of calculations. The calculated XRD patterns are normally fitted to the observed XRD profile using least square analysis. Ultimately the optimum phase scales for a best fit are generated. The scales are then used to determine the percentages of the amount of different minerals present in the coals. Ural (2007) has extensively used Rietveld method to quantify mineral in coals, excluding South African coals. Computer control techniques using software's like SIROQUANT are used to do mineral quantifications. The software is the realisation of Taylor in 1991 (Ward *et al*, 1999, 2001a; Ural, 2007). Ward *et al* (1999, 2001) and others have extensively used the package and came to the conclusion that, the Taylor method is consistent, after doing a work cross check with other researchers that used the same software. XRD technique was used in this research for the identification and quantification of minerals present in coal samples that might influence abrasion.

2.9.4. Scanning electron microscope

The scanning electron microscope (SEM) is one of the back bone techniques used today for coal analyses. The technique is employed on industrial and research levels for the characterisation of minerals in coals, their shape and the morphology of coal particles. SEM techniques unlike optical microscopes are useful for characterising fine minerals in coals. Unlike microprobes which have been unable to study mineral matter in coals less than lo microns, SEM techniques are able to resolve or analyse the fine grains (< 10µm) of minerals present in coals. The stated capabilities, particularly of mineral identification at fine level, are induced by energy dispersion X-ray (EDS), which makes it possible to quantify and analyse fine grains of mineral matter in coals. It is for these reasons that it has been greatly employed in the coals industries for mineral matter characterisation. Their advantage over optical microscopes and microprobes is therefore that, SEM techniques are enabled by EDS to have a wide range of magnification, a great depth of focus and good resolutions. SEM techniques are automatic making them rapid when compared to conventional techniques (Creelman and Ward, 1996).

SEM techniques have also been used for characterising organic constituents of coals (Finkelman and Stanton, 1978). However van Alphen (2007) insists that SEM is unable to identify all the macerals present in coals. This limitation is induced by the technique since it uses electrons for identifying macerals. Optical techniques use white light which enables their accuracy for macerals identification. The accurate macerals identification is based on shades of grey, with liptinite appearing almost black and fusinite white.

Different kinds of scanning electron microscopes technique exist today with different designs, analytical procedure and data processing softwares. These SEM techniques include computer control scanning electron microscope (CCSEM), scanning probe microscope, scanning electron microscope with energy dispersive X-ray (SEM-EDS) and quantity scanning electron microscope (QEM*SEM/QEMSCAN). All these SEM techniques however are based on SEM principles and use X-rays to discriminate minerals present in coals, with a suitable micro-analysis, with good image processing units. Of all these types the two most important SEM techniques for the quantification of minerals in coals are SEM-EDS and QEMSCAN.

The development of QEMSCAN as used in the coal industry is discussed in details by van Alphen (2007). Creelman and Ward (1996) detailed a study on the quantification of minerals present in coals using SEM-EDS. Huggins *et al* (1982) have described a system in which the morphology and size of mineral grains in the polished block of coal can be determined. The shortcomings of these analyses procedure include the fact that SEM*EDS cannot discriminate between the macerals of coals and the epoxy resin in which it is mount (Creelman and Ward, 1996).

Scanning probe microscopes has been used by different researchers to effectively discriminating between types of abrasive wear (e.g. Misra and Finnie, (1980)). Hutchings (2002) used SEM techniques to study the topography of abrasion damaged surfaces. By studying the topography of abraded surfaces it was possible to establish the kind of abrasive wear that had occurred during grinding. Meaning that, it was possible to discriminate between the two abrasive wear as indicated in Section 2.5. A three-body abrasion wear will have a surface with multiple scratches of no significant origin whilst a two-body abrasion system surface abraded will materialise with linear grooves which are non-distinct (Hutchings, 2002). Toporov (1960) and Rabinowics *et al* (1961) concluded that linear grooves on the abraded surface are always due to a hard particle that is immobile (or stationary).

The SEM photographs or micrograms shown in Figures 5, 6, 7 were used distinctively to distinguish between the two abrasive wear as discussed in section 2.3. It is evident from the pictures that the distinction, following on Hutchings, Toporov, Rabinowics and others, between the abrasive wear is simple with SEM pictures.

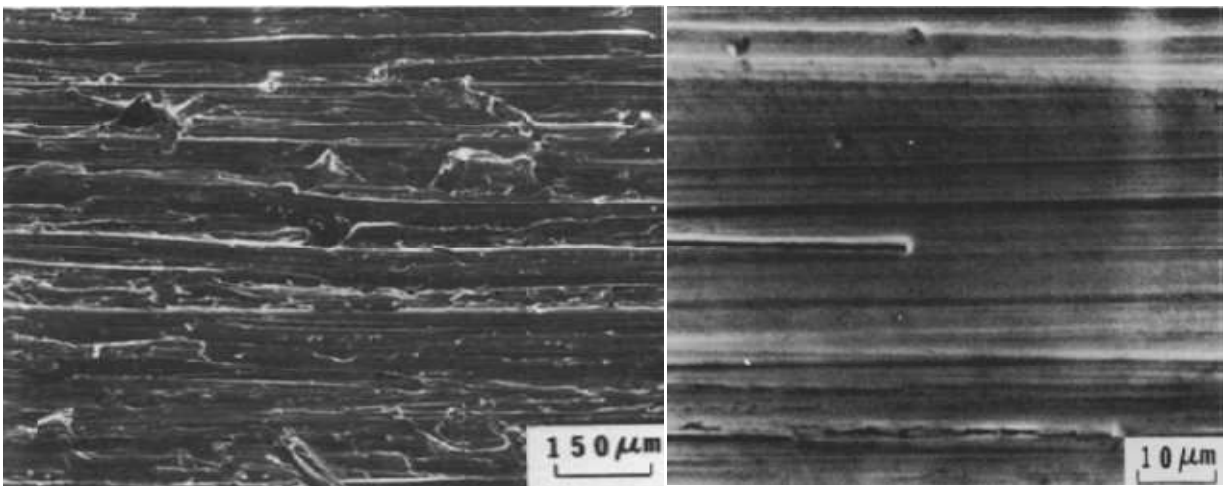


Figure 5: Two-body abrasion wear (Misra and Finnie, 1980)

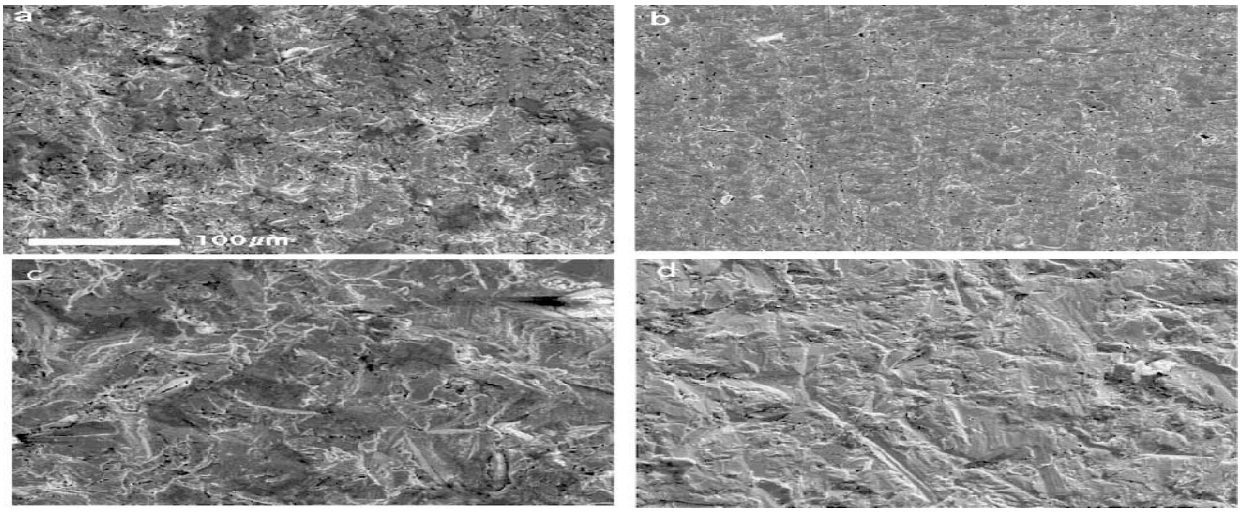


Figure 6: Three body abrasive wear micrograms (Stachowiak and Stachowiak, 2001)

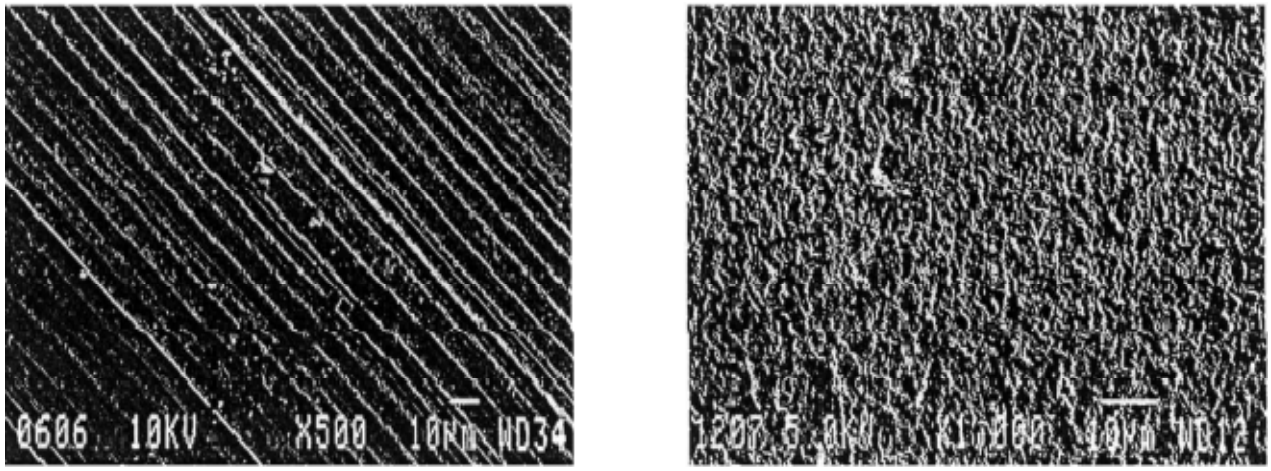


Figure 7: Micrograms differentiating between two-body and three-body abrasion wear respectively (Hutchings, 2002)

Figure 7 distinctively differentiate between grooving and rolling abrasion respectively. Lines of particular directions or defined orientation will exist on an abraded surface, as for three body abrasion multiple indentation of no orientation or undefined origin exists. These observations are supported by both Figures 5 and 6 respectively. SEM-EDS technique was used in this study for the characterisation of the blades making it possible to classify the kind of abrasive wear that resulted during grinding of coals, and for the determination of particle morphology and shapes and chemical analyses.

2.10. Coal mechanical properties and power

Comminution has long been studied for many different reasons. These reasons include surface area analysis, power-energy consumption, and grinding and/or abrasiveness nature of coals. For this study power was studied so to determine coal grinding properties that may influence abrasion. These grinding properties include abrasion factor and abrasion intensity. Abrasion factor is defined as weight loss of the grinding blades divided by the pulverised coal weight, and abrasion intensity is determined by dividing the mass of the pulverised coal by the surface area of the blades exposed to grinding multiplied by the time it takes for the grinder to reduce the feed coal. Power consumed by mills is dependent on the mechanical properties of coals.

Coal hardness, grindability, abrasiveness, friability, etc are commonly known as coal's mechanical properties (Speight, 2005). Hardness, friability, tenacity and fracturing are closely related to grindability of coals (Tichanek, 2008). HGI is a function not only of hardness, but also shearing i.e. natural fracturing of coal (Speight, 2005). Shearing of particles is dependent on the type of mill used (Sahoo, 2006). The degree of pulverising is determined using index of comminution (IC) (Scieszka, 1987, 1985, 1996; Spero *et al*, 1991). This index measures the degree at which grinding occurred in mills (Sahoo, 2006). Size reduction by any mill is proportional to the energy used by a mill to achieve a small coal particle (Tavares and King, 1998). The energy can be calculated from HGI values using the Bond Index (W_i) and HGI relationship (Tichanek, 2008).This energy is important to know, since the higher the power of consumption, the harder was the material to grinding (Tavares and King, 1998; Tichanek, 2008).

Abrasiveness is also relatable to grindability of coals. Abrasiveness is the propensity of a coal or ore to wear away grinding equipment's. AI and HGI were established to exist in close relation (Sciezska, 1985). Since wear and grinding go together, both can influence the energy or power utilised by the mill to pulverising coals, particularly grindability nature of coals. This factor is well established in literature where it is supposed that high power consumption is directly related to hard grinding material which will in return result in high wear.

Power consumption by mills is very important to establish because of heavy costs relating to its use and loss by inefficient mills. Mass balances are also very important because feed rates are proportional to the efficiency and throughput of mills (Scieszka, 1996; Chenje and Radziszewski, 2004; Al-Thyabat and Miles, 2006; Eswaraiah, 2008) and the finest ground mass can directly be related to power consumed by a mill. Nikolov (2002) has shown a detailed model for the mass balances for impact crushers. For YGP mills there is little or no information on their mass balances. Even though this is important it did not form part of this study and will not be discussed further.

Power consumed by mills can be explained to be linear at first, and constant with time (Chenje and Radziszewski, 2004; Radziszewski *et al*, 2005; Sahoo, 2006). This is said because mills are known to use a lot of power at early stages of comminution (Chenje and Radziszewski, 2004; Sahoo, 2006). Sahoo (2006) stated: "The degree of breakage increase with an increase in the

impact velocity up to a certain impact velocity depending on the material characteristics". This statement is supported by Eswaraiah (2008), where the effects of speed (rpm) on the particle size produced were investigated. At steady state, the power consumed seems to be constant. Steady state means power consumption by mill is constant at constant velocity (Scieszka, 1996; Eswaraiah, 2008). A schematic description of such event is given in Chapter 4, Figure 22.

Power used by mills to crush can be determined using devices measuring power, but, the most commonly used techniques are mathematical models. Mathematical models for power consumption by mills are well established. These models are not applicable to calculating energies of all mills, but are specific to the mill type. Power-energy models differ from one mill to another because of conditions imposed and quantities used in developing such models (Sahoo, 2006). For instance, some authors use mill properties such as radius, combined weight of mill and feed material and the rotational speed for the power-energy models development (Nikolov, 2002). Other authors use torque (τ), heat (Q) gained or lost, and the sound or noise a mill makes during milling to develop or design energy models for that particular mill or grinding machine (Chenje and Radziszewski, 2004).

Scieszka (1985) developed a model for the abrasion Tribo-tester mill. This model can simply be called an integral energy input model. This model was developed using time intervals and the differential torque. One needs to realise that power is a function of energy with time ($\frac{dE}{dt}$), therefore by determining one, the other will be by integration. Noise is dependent on applied force or torque (Chenje and Radziszewski, 2004). Noise will increase with torque when the angle of abrasion decreases (Radziszewski *et al*, 2005). For this study torque was used for the energy calculation. This is because the abrasion tester pot arm's, on which the blades are hooked, rotate when grinding coals. A model by Scieszka (1985) was used herein without modifications for the determination of energy and power consumed by the YGP abrasion index tester mill during comminution.

In comminution, two-energy calculations approaches are normally used to understanding energy to particle size relation, which is directly relatable to power-consumption and mill efficiency. The two approaches are well explained in Stamboliadis (2007), together with their short-comings. The two approaches are those by Kick (1885) and Rittinger (1867). These approaches are frequently used in literature, but Stamboliadis (2007) has given a different view on these approaches, and considers them to be confused, even in the relevant textbooks and published research works.

The first approach by Kick (1885) states that the energy required to break a particle of certain material is proportional to its mass. The second approach by Rittinger (1867) states that, the energy consumed during grinding is proportional to the newly produced surface (Staboliadis, 2004, 2005, 2007). That is, power-energy consumed by a mill is proportional to the surface area of the target PSD. The scrutiny on the shortcomings pertaining to these two approaches is given in Stamboliadis (2005) and Tavares and King (1998), where both the theoretical and experimental approaches are given by the respective authors.

2.11. Summary of literature review

In this Chapter coal constituents that are known to induce abrasiveness of coals as discussed by different researchers are discussed. Different analytical techniques use to characterise the ROM coals were introduced. This section introduced different kinds of mills and the types of comminution mechanism utilised by each grinder during coal grinding. The mill used for this study to test coals for abrasion uses attrition mechanism. Minerals in coals such as quartz and pyrite, and others that influence AI of the coal samples were discussed. Also this chapter concluded that coarse particles will always lead to abrasion following on the discussion on PSD and SEM. SEM photographs showing different abraded surface topography were displayed for use in establishing the difference between two-body abrasive wear and three-body abrasive wear. In addition, power utilised by mills is discussed and it is clear that power is dependent on both abrasiveness and hardness of coals.

CHAPTER 3: EXPERIMENTAL

3.1. Introduction

A set of five South African ROM coals were used in this study. These coal samples were obtained from Eskom's research facilities (ERIC) in Roscherville and represent the coals from the Witbank Coalfield. These coals were identified as Coal A, Coal B, Coal C, Coal D, and Coal E. Traditionally, to understand different properties of coals and relate them to different coal applications, coals must be characterised for both their chemical and physical characteristics. For this study eight different analytical techniques were adopted, based on the premise that they can contribute information that can make it possible for this study to adequately reveal coal constituents that cause abrasion during grinding.

Traditionally coals are characterised in terms of proximate analysis (TGA method) and X-ray fluorescence (XRF). These techniques form the basis of all the techniques used in coal research, because they are easy to use and mostly available on a laboratory scale. Owing to the heterogeneous characteristics of coals the traditional techniques may be inadequate in predicting the behaviour during different coal applications. Further techniques are required to better the understanding of the coals and their potential use. These techniques may include microscopes such as scanning electron and petrography microscope, advanced X-ray techniques such as Powder X-ray diffraction and others. Their applicability to coal research has lead to wealth of information being derived from coal seams. Techniques such as an abrasion index tester and Hardgrove machine are also used as characterisation techniques particularly were coal comminution is important in the mining industry and for coal trades.

For this study a Perkin-Elmer TGA, a Labcon moisture oven, an abrasion index tester pot, Hardgrove machine, petrographic microscope, SEM- EDS, XRD and XRF were used. XRF was used for the kinds of ash oxides that were present in coals. Petrography was used for the determination of minerals, rank, macerals, oxidation and microlithotypes of the selected coals. XRD was used to qualify and quantify minerals that were present in all coals. SEM-EDS was

used primarily for the characterisation of particle morphology and shape and to characterise the surface topography of the blades used as cutting elements. The abrasion index tester pot and Hardgrove machine were used to determine AI and HGI of the coal samples respectively.

3.1.1. Sample Preparation

Coals are normally received on dry or wet basis. For an effective study regarding crushing or grinding of materials, materials have to be dry. Received samples were first weighed as received, and then left overnight at room temperature and atmospheric pressure to dry in a tray. This allows for the determination of residual moisture or surface moisture. This way of determining residual moisture is described in Lenahan and Murray-Smith (1986). The air-dried bulk samples were coned and quartered into four representative portions. A quarter was set aside, to serve as a primary parent sample. The other quarters of the dried samples were combined and then milled to particle size of -1470 +850 µm, which was used as bulk parent coal. From the bulk coal sampled sized to -1470 + 850 µm, the quarter on which chemical analysis were carried was set aside. The bulk of the material went into testing for AI and HGI.

3.2. Proximate analysis

A Perkin-Elmer simultaneous thermogravimetric analyser (STA 6000) equipped with Pyris manager software was used to determine the proximate analyses on the bulk coal samples sized to less than 75 µm. Proximate analysis is an analysis that gives information about percentage (%) moisture, volatile matter and ash content in coal samples. The percentage fixed carbon (%FC) is determined by subtracting the other results from 100 %. That is, FC %=100-(%moisture+ %ash+ %volatile matter). This equipment was used in the Coal Research Laboratory of the University of the Witwatersrand, School of Chemical and Metallurgical Engineering.

3.2.1. Sample Preparation

The cone and quartered sample from the bulk parent coal samples (-1470 + 850 µm) was used to prepare a sample for the analysis. The samples were crushed then sieved to achieve a particle size less than 75 µm. The sieved sample was sealed in a container so as to prevent atmospheric

moisture from interacting with it. It is known that due to enhanced surface area fine crushed coal particles are more susceptible to moisture than bigger particles; hence it is advisable that immediately after crushing, samples must be sealed. The prepared samples were used for proximate analyses determined by TGA as described below.

3.2.2. Experimental Procedure

Before commencing with the proximate analysis, a water bath connected to the TGA was switched on until a temperature of 10°C was attained. This is to ensure that the cooling temperature remains constant throughout the run. 5-15 mg of a representative sample was loaded into a pre-weighed ceramic crucible for the analyses. The weighed sample was then stabilised at room temperature for at least three minutes in a constant inert atmosphere inside the TGA furnace. Before the start of the combustion reaction, the sample temperature was allowed to equilibrate with the furnace temperature. The temperature of the furnace was ramped at 50°C/min (heating rate) to 900°C/min in an inert atmosphere, holding at 900°C for seven minutes. At this stage the inert atmosphere was replaced by oxygen with the furnace remaining at 900°C for a further 20 minutes. Gases were allowed to flow at a flow-rate of 20 ml/min at atmospheric pressures (Lenahan and Murray-Smith, 1986; Morgan *et al*, 1986). The gases used for proximate analysis are nitrogen and oxygen respectively.

3.3. Moisture analysis

A Labcon laboratory oven was used for the determination of analytical moisture. A thermometer was fixed to the inside of the oven which monitored the heating temperatures, kept between 105°C and 110°C. Moisture determined in this fashion is called inherent or residual moisture (or analytical moisture). A conical container with a lid was used for mass loss determination. The difference in mass of the container with the lid and the coal before and after heating was taken as the moisture lost. The moisture was reported in percentage (%). This equipment was used in the Coal Laboratory of the University of the Witwatersrand, School of Chemical and Metallurgical Engineering.

3.3.1. Sample Preparation

Coal samples were ground using an automated Monitor and Control Laboratories (MCL) grinder, and then sieved using an automatic shaker. The sieve's apertures from which a representative sample was derived were -212 µm and + 150 µm respectively. The samples were contained in sealed bottles to prevent moisture from being absorbed from the atmosphere (Lenahan and Murray-Smith, 1986). Moisture analyses were carried out as described below.

3.3.2. Experimental procedure

A conical sample container with a lid was used to carry out this test. One gram (g) of prepared coal (-212 µm and + 150 µm) was loaded into a sample container and weighed accurately using a calibrated weighing balance. The weighed sample was introduced to the oven at a temperature ranging between 105°C and 110°C for 1hr and 30 min. After this period the sample container was closed, removed from the oven, and then placed into the desiccator for cooling. After several minutes the sample was taken out of the desiccator to the weighing balance. The moisture loss was determined by mass difference (ΔM). Percentage moisture was determined by dividing ΔM by the load mass all in grams (g). The difference between the initial and final mass of container plus a lid was taken then divided by 1g to get percentage moisture lost by the coal sample. Several trials were conducted, the aim being to establish the accuracy of the method (Lenahan and Murray-Smith, 1986) and so as to determine representative results.

3.4. Abrasion index



Figure 8: Abrasive index tester pot

The AI was determined by use of YGP abrasion index tester pot. A 203±0.25 mm internal diameter and 229±0.25 mm deep steel pipe constructed AI tester pot fitted with an electric motor and a revolution counter was used, which measures the number of revolutions the rotor completes when grinding samples. The pot was designed to rotate at a constant speed of 1470±30 rpm for set number of revolutions. For the determination of AI 12000 revolutions were set. The pot had rotating arms on which cutting blades were hooked. The blades of 38.0±0.1 mm×38.0±0.1mm by 11.0±0.1mm when new, with a hardness of 160±15 (Vickers hardness pyramid number) were used. The blades are made from iron materials. This equipment was used in the School of Extraction Metallurgy, University of Johannesburg (UJ), Doornfontein.

3.4.1. Sample preparation

The samples used for the AI analyses were derived from material prepared as explained in section 3.2. A sample of particle size range of -4750 µm and +850 µm was used for the analyses. Of the -4750 µm and +850 µm bulk sample achieved, 2 kg was used for the test. Before the AI test could commence, a 2kg sample was analysed for proportion of included fine particles. This was achieved by sieving the 2kg sample so to ascertain how much sample passed the 75 µm sieve. The fines were returned to the parent sample. The masses were used to determine the

index of comminution (IC) for each coal sample following Sciezska (1985). Two or three trials were conducted depending on the success of the test trial.

3.4.2. Experimental procedure

A two way procedure was adopted. The initial testing involved the conditioning of the blades. This is a recommendation for blades used in the determination of AI of coals or any materials. The second procedure involved the actual determination of the coal's abrasion indices. The two procedures are outlined below:

Conditioning procedure: Blades used for the AI test had not been used before. They were still new and they had to be conditioned as recommended. Blade conditioning involves the use of a portion (at least 1kg) of prepared coals sample to be tested. Blades fixed to the rotating arms were rotated at 1470±30 rpm for 12000±20 rev. These blades were weighed before and after conditioning. If a coal of a known AI was used for conditioning, then the AI obtained has to be repeated until that value is attained. In this study, since the abrasion indices of these coals were not known, the conditioning process was done twice for every set of new blades used. After the conditioning process, the blades were washed with methylated spirit and a hard brush so as to get rid of all coal particles that might have clung to the blades. The washed blades were oven dried and let to cool to ambient temperature, then weighed on a calibrated balance to determine the initial mass of the blades to be used in the second procedure.

Abrasion index procedure: Having properly hooked the newly conditioned blades of known mass to the revolving motor of the mill pot, a 2kg coal sample was introduced into the deep constructed steel pot, which served as a container. The feed coal was thoroughly levelled out over the blades. The pot was covered with a steel lid, so as to prevent loss of coal particles during comminution, and then the counter was set to zero revolutions.

The initial temperature of the tested sample was taken using a thermometer (recommendations are that a thermocouple be used). The temperature readings are used to calculate the bed moisture of coals tested for AI (Spero, 1990). Having introduced the sample into the pot, the revolving counter was set for 12000 rev. A start button was pressed simultaneously with the stop

watch to record the time it takes for the mill to come to rest. At the completion of the 12000 rev the blades were checked to determine if they were still intact. This is done so as to be sure that all blades did take part in grinding; otherwise the overall AI would be incorrect, since all four blades are used to determine the AI of coals. After this the blades were ready for cleaning, drying and weighing. The final temperatures were recorded at 3 minutes. The ground coal was left to dry at room temperature then contained. Mass loss of the blades after grinding and their initial mass were used together with the feed mass to calculating the AI. The product coal was sieved into four different fractions, ranging from -1470 µm to – 75 µm and further characterised using SEM-EDS and XRD.

3.5. Hardgrove grindability index

To complement the AI data, it was necessary to determine the HGI of the coal samples under examination. The equipment used for the test is located at Witlab, Witbank, South Africa. The model number was not available.

3.5.1. Sample preparation

Coals were crushed and sieved to -3000 µm as required by Witlab. Further preparations were carried out at Witlab (in-house method was used).

3.5.2. Experimental procedure

Coals sent for HGI tests were analysed using ASTM-D409-51. Typically this method utilises a machine that used eight steel balls as cutting equipment. Fifty grams of coal is loaded then ground by rotating the machine at 60 rev/s. The product coal is sieved such that material can pass through a 200 mesh (75 µm). Material passing the target sieve is taken to be the HGI of that particular coal.

3.6. Petrography

A Leica DM4500P petrographic microscope was used for the optical determination of the organic and inorganic components of the coal samples. The microscope has a stage which allows the positioning of the coal block under the objectives for efficient viewing. A digital camera is available to take pictures of particular sections of the coal block. Coal blocks were analysed for minerals, rank, oxidation condition, microlithotypes and macerals. Analyses were conducted in the laboratory of the University of the Witwatersrand, School of Chemical and Metallurgical Engineering, by Professor Nicola Wagner.

3.6.1. Sample preparation

Coals derived from the coned and quartered bulk materials (parent coal) were ground to particle size of -1000 µm following standard petrography procedure ISO 7404/2 (1998). The blocks were prepared by mixing coal particles (-1000 µm) with resin and hardener. The mixture was allowed to solidify under ambient temperatures and atmospheric pressure. Prepared coal blocks were polished using a Struers TegraForce-1 polishing machine. This is done so as to achieve a scratch free surface.

3.6.2. Experimental procedure

The coal blocks were immersed with an oil droplet on the surface before being analysed for their organic and inorganic components under a microscope. The immersion oil enhances the coal reflective index under the microscope. The macerals were analysed following ISO 7404-3 (1998) standard; rank was analysed for following ISO 7404-5 (1998); and the microlithotypes were analysed following ISO 7404-4 (1998) standards. Minerals which are characterised as rocks or minerals grouping were also determined. The analyses were conducted at magnifications of X500 under reflected polarised light.

3.7. X-ray fluorescence (XRF)

X-ray fluorescence is a technique traditionally used to characterise the ash oxides in coals. Before it can be used, coals have to be ashed. Subsequent to ashing, the actual characterisation of coal ash oxides using XRF technique is performed on the ash. This analysis was undertaken by Witlab, Witbank, South Africa.

3.7.1. Sample preparation

Coals were crushed and sieved to -3000 µm as required by Witlab. Further preparations were carried out at Witlab (in-house method was used).

3.7.2. Experimental procedure

In house Witlab procedures were used for the ashing process and the determination of coal ash oxides (Witlab In house method).

3.8. X-ray diffraction (XRD)

A PANalytical X'Pert Pro powder diffractometer with X'Celerator detector and variable divergence- and fixed receiving slits with Fe filtered Co-Kα radiation was used for the qualification and quantification of minerals present in coals. This technique was used in the laboratory of the XRD Analytical and Consulting, Pretoria. The analyses were conducted by Dr. Sabine Verryn.

3.8.1. Sample preparation

Parent coal samples derived from the bulk coal sample of particle size -1470 + 850 µm were used for the analyses. This parent coal samples were crushed and sized to -75 µm using an automatic grinder. The product coal samples sieved and size to + 75 µm were also prepared. Both coal sample types were further finely ground using a pestle and mortar. These samples were prepared for XRD analyses using a back loading preparation method.

3.8.2. Experimental Procedure

The prepared samples were placed in the sample contained then into the XRD chamber for the analyses. The sample phases were identified using X'Pert High score plus software. The relative phase amounts reported in weights percent were estimated using the Rietveld method (Autoquan Program). All samples were analysed for the errors. For every sample analysed, a diffractogram was taken. The diffractograms were recorded in a scan range of 5º 2θ to 100º 2θ, at a scan rate of 0.02 2θ which took 10 minutes.

3.9. Scanning electron microscope (SEM)

FEI Quanta 200 scanning electron microscope fitted with an Oxford INCA 400 energy dispersive x-ray (SEM-EDS) was used to qualify and quantify the minerals that were present in the coal samples. The coal particles were characterised for their shape and size, and also where possible for their oxidation status. Coal samples are rendered oxidised when their particles appear bright under the microscope. The coal particles were excited using a tungsten filament laser which produced 1500K electrons per second. Liquid nitrogen was used to keep the SEM-EDS sample loading chamber under inert environment. This technique allows semi-quantification and qualification of minerals present in coal samples. The instrument used calcium carbonate, iron sulphide, silica, magnesium oxide and aluminium oxide standards. This technique is semi-quantifying, owing to the fact that a 10% deviation is possible when analysing for minerals. The instrument is located at the North West University, School of Chemical and Mineral Processing, Potchefstroom campus. The analyses were conducted by Professor Louwrens Tiedt.

3.9.1. Sample Preparation

A representative sample derived from the bulk parent coal was crushed and sieved to less than 75 µm. Coal particles were stuck on a black tape, and then coated using a copper strip. The reason why finely ground coals were used as opposed to blocks is that, blocks needed to be coated with carbon fibres, which eliminates the determination of carbon materials present in coal samples. The use of copper strip allows the determination of carbon in coal samples, and all minerals that are rich in carbon. This can be achieved without excess carbon being reported.

3.9.2. Experimental Procedure

The copper coated samples, both the parent and product, were placed inside the high pressure vacuum chamber of the SEM unit. This allowed the sample to be in equilibrium (or stabilise) with the environment under which it was to be analysed. The vacuum will normally lower the pressure, indicating that the instrument has stabilised and is ready for use. Attached to the SEM unit is a liquid nitrogen cylinder which allows for the SEM unit to be in an inert environment. The SEM unit has a digital camera from which pictures are captured. The picture can indicate the shape and morphology of the coal sample particles analysed. After the picture of the sample sections were taken, the coal samples were analysed using SEM back scattering image for their mineralogy. EDS used for mineral quantification was allowed an excitation energy of about 15.0 kV. This system had X400 magnification, but, different magnifications were used for better resolution. The instrument was allowed an acquisition time of about 100 seconds. Ten thousands (10000) counts were taken across the unit area of every sample that was analysed.

Surface topography of the cutting blades was characterised using SEM in the University of Pretoria by Mr. Josias van der Merwe. Similarly, the blades were placed on the stage under the objectives, then characterised using different magnifications for the best resolution.

3.10. Particle size distribution

Particle size distribution was conducted on the product coal using a sieve method. Product coal here refers to the coal that came out of the abrasion index tester pot. Sieve method gives class coal particles according to their size. The meshes used were 1470 µm (top size), 850 µm (middle class), 150 µm (limiting sieve) and 75 µm (bottom size).

3.10.1. Sample preparation

Coals received from the pot were noticeably wet. These samples were dried overnight at 105°C and atmospheric pressure. This was to prevent agglomeration and inefficiency in sieving. The dried samples were weighed before using a calibrated weighing balance. This analysis was

carried out using the automatic shaker and sieves in the Laboratory of the University of the Witwatersrand, in the School of Chemical and Metallurgical Engineering.

3.10.2. Experimental procedure

The dried coal samples were sieved using the automatic shakers and sieve of size stipulated above. Thirty minutes was allowed for the shaker, which shook at frequency of 3 MHz. After shaking the coal samples were weighed according to their size class. Note that this method is not efficient, as loss of coal mass is bound to happen and the efficiency is dependent on the ability of the researcher using it. But, the efficiency was at least to some degree ensured. To ensure that most of material had separated a brush was used on the screen.

3.11. Power calculations

Power calculations were done using empirical formula as described in literature. To do the calculations, AI values obtained from Section 3.5 and particle size distribution masses determined in Section 3.11 were used to calculate the power used by the abrasion index tester pot to grind the coals.

3.12. Summary and conclusions

The chosen techniques are used here following their ability to identify, qualify and quantify minerals and their associations, moisture and ash in coals, which are deemed the greatest abrasive constituents of coals. The ability of SEM to indentify these minerals, as well as revealing their morphology and shape makes it an important tool for this study. This is because mineral strength, shape, size and orientation together can enhance one’s understanding on the abrasive quality of coals. Power utilisation in engineering applications is very important aspect hence it was calculated for in this report, also power utilised by the pot during grinding helps to understand the grinding properties of the coals.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1. Introduction

The results discussed in this section were obtained using a series of analytical techniques as discussed in Chapter 3. These analytical techniques were selected with an understanding that they will be able to produce results that would help conclude the aims of this study. Literature review given in Chapter 2 outlined in details the use of these selected analytical techniques in enhancing the understanding of coal abrasion in comminution. Using the selected analytical techniques and procedures as outlined in Chapter 3, five South African ROM coals from the Witbank Coalfield were characterised for organic and inorganic constituents. The grinding properties of the five coal samples were also determined, along with proximate analysis, moisture analysis and particle size analyses. The results are reported below together with the discussions and findings.

The results and their discussion are given in this order:

- Proximate analysis
- Moisture
- Abrasion
    - Abrasive wear and AI
- Effects of total moisture on AI
- Effects of HGI on AI
- Petrographic components and impacts on AI
    - Macerals and vitrinite reflectance
    - Petrographically determined minerals and impacts on AI
    - Microlithotypes and impacts on AI
- Chemical analysis
    - X-ray fluorescence spectroscopy
    - X-ray diffraction (and primary minerals that impact on AI)

- Scanning electron microscope used for particle morphology characterisation
- Particles size distribution analysis and impacts on AI
- Abrasiveness, Grindability and Energy

4.2. Proximate analysis

Proximate analysis is a conventional method of coal analysis used in coal research. The coal samples were analysed for % total moisture, volatile matter, ash and fixed carbon (by difference) using thermogravimetric analyser (TGA). Results are reported in Table 1.

Table 1: Proximate analysis (%, as received)

Coal Name	Moisture (%)	Volatile matter (%)	Ash (%)	Fixed carbon (%)
Coal A	3.7	25.4	30.7	40.2
Coal B	4.4	26.7	38.6	30.3
Coal C	2.6	23.5	41.2	32.7
Coal D	2.4	27.5	42.0	28.1
Coal E	2.2	31.5	33.6	32.7

From Table 1 it is evident that Coal B has the highest moisture content, followed by Coal A. Coal E has the highest volatile matter, and Coal C and D have the highest ash. In summary these coal samples are high in ash (which is above 30%) and probably a typical average volatile matter content for South African coals.

4.3. Moisture

Moisture is a typical coal constituent that is known to cause abrasive wear. Three types of moisture were determined here-in. It has to be noted that generally total moisture constitute both free moisture and inherent moisture (Lenahan and Murray-Smith, 1986; Eswaraiah*et al*, 2008). Total moisture therefore is the only component that is used later to establish the effects of coal moisture on coal abrasive quality. Total moisture is defined as the moisture present within the coal matrix, in all forms, excluding water of crystallisation (Speight, 2005). Results are reported in Table 2.

Table 2: Moisture contents of coals

Coal name	Free moisture (%)	Inherent moisture (%)	Total moisture (%)
Coal A	2.2	4.3	6.4
Coal B	5.9	4.9	10.2
Coal C	1.9	2.5	4.3
Coal D	1.5	2.5	3.9
Coal E	1.8	3.0	4.7

From Table 2 it is evident that Coal B has the highest overall moisture, followed by Coal A. Coal D has the least total moisture, with Coals C and E having equivalent total moisture. Table 1 and Table 2 show similar trends on the reported moisture values. The difference in the reported values, which are not that different, is that the moisture values reported in Table 1 can be accurate as they were obtained using TGA, which has a well controlled atmosphere which offers no temperature fluctuations as oppose to the Labcon moisture oven which might not have been so well controlled realising that the temperatures fluctuated between 105 °C-110 °C. The sample

weight might have also affected the reported moisture values since TGA uses micro-grams of a coal sample weight whilst the moisture oven uses a gram of a coal sample.

The results from both Table 1 and Table 2 indicated that coal moisture is best reported as total moisture, since both inherent and surface moisture forms part of the coal structure. Therefore when the coal is utilised or ground, it is the overall moisture which will impact on the process. This suggestion is also based on the reason that total moisture may carry some degree of accuracy as opposed to inherent moisture. The latter moisture is calculated using approximations, whereas total moisture is accurate as conversions are taken into account when it is reported. These conversions can eliminate errors, both experimental and apparatus errors (see appendix B, equation B2). Total moisture values reported in Table 2 will be used for comparative purpose in this report.

4.4. Abrasion

Before reporting the AI values of the coal samples, it was important that the wear on the blades that resulted during coal grinding using an AI tester pot be ascertained. This was one of the objectives of this study. The kind of abrasive wear and the AI values are discussed in separate sub-headings below.

4.4.1. Type of abrasive wear

Two types of abrasive wear are addressed in Chapter 2. Abrasion occurs during comminution as a result of friction (Austin *et al*, 1984). In commercial plants abrasion occurs due to different kinds of minerals which are harder than material used to construct mills and its grinding elements. Shown below are the SEM photographs taken from a fresh and an abraded surface of the blades that were used as cutting elements when coal samples were tested for abrasion.

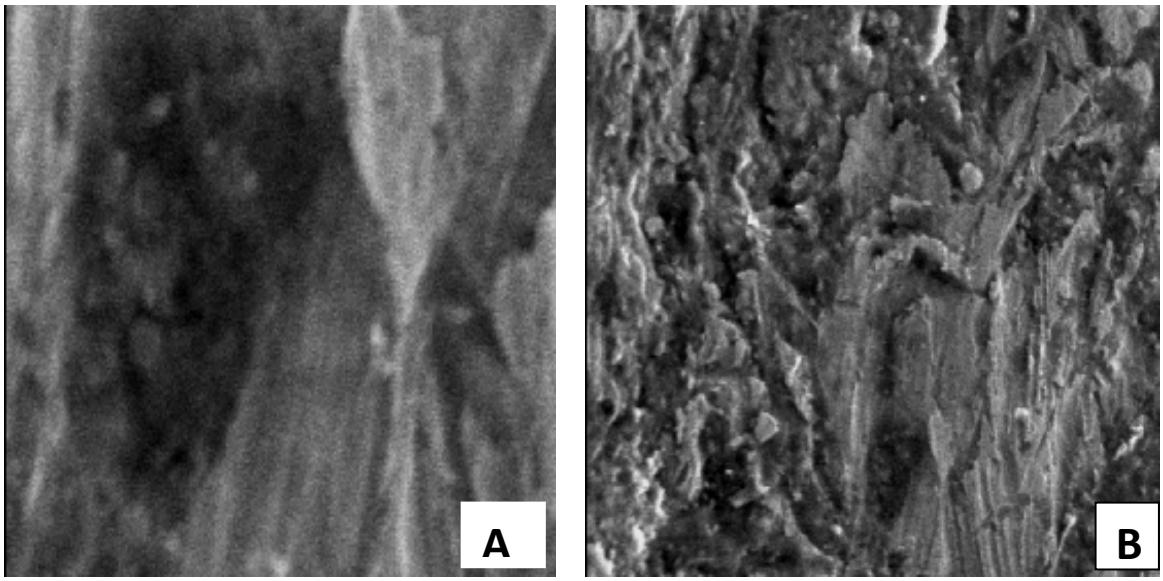


Figure 9: SEM-EDS photographs of iron blades worn by coals

Figure 9 represents the photographs taken on both new and used blades. Picture A represents the SEM results obtained from the new blade; Picture B was taken on the used blades. Picture A shows smoothness to some degree as blades were new but were observed to be rusty; the dark spot on Picture A is rust. Picture B shows pitting and grooves as a results of coal particles being ground in an AI tester pot which used impact and attrition mechanisms for grinding. These digital back-scattering images were taken at 450* and 1900* magnification, randomly across the surface of the blades, respectively. Picture B was used to conclude that the resulting abrasive wear during coal grinding in the AI tester pot was three-body abrasive wear.

This conclusion is based on the established theory that two-body abrasive wear is distinguishable from three-body abrasive wear by an abraded surface that has line grooves which will have point of origin and/or are consistent with defined structure, while three-body abrasive wear is identified by line grooves of no origin, primarily by pitting (See Chapter 2,Section 2.9 for the supporting evidence).

4.4.2. Abrasion index

Abrasion index values reported in Table 3 were obtained using the AI tester pot following the YGP method as described in Chapter 3.

Table 3: Abrasion index values

Coal name	Abrasion index (mg/kg)
Coal A	87.35
Coal B	115.58
Coal C	28.63
Coal D	85.70
Coal E	51.15

Results reported in Table 3 suggest that Coal B is most abrasive of all coals; the least abrasive is Coal C. Since coal's AI is affected by different constituents of coals, it is necessary therefore to discuss AI further with other results obtained; chemical and physical constituents. This will help by paving a way in which the coal constituents that influenced the reported AI values can be deduced or inferred. This will be obtained by making effective correlations between AI and chemical and other physical constituents. In the next sub-sections of this chapter, this grinding property of coal (abrasiveness) is discussed together with results obtained from different analytical techniques that were used for characterising coal samples; this was in order to address the main aim of this research.

4.5. Effects of total moisture on AI

Several researchers doing different work agreed that an increase in coal moisture will result in an increase in abrasion or wear rate of grinding elements (Coldham, 1989). Table 4 reports AI values and total moisture for the coal samples.

Table 4: Abrasion Index and total moisture

Coal name	Abrasion index (mg/kg)	Total moisture (%)
Coal A	87.35	6.4
Coal B	115.58	10.5
Coal C	28.63	4.3
Coal D	85.70	4.0
Coal E	51.15	4.8

Coal B, which has the highest total moisture, has the highest AI value of all the coal samples. Coal C has the low moisture and has low AI value respectively. Coal A has the significant total moisture value, next after Coal B, and it also has a high AI value after Coal B. Coal C and Coal D have equal moisture values, but their abrasiveness is largely variable. From Table 4, particularly looking at Coal E which has moisture greater than Coal D but least abrasive, it was difficult to fully establish if moisture influenced AI of the coal samples. To ascertain this observation and the observations made by Coldham (1989) and others, a correlation between AI and total moisture was drawn. This is shown by Figure 10.

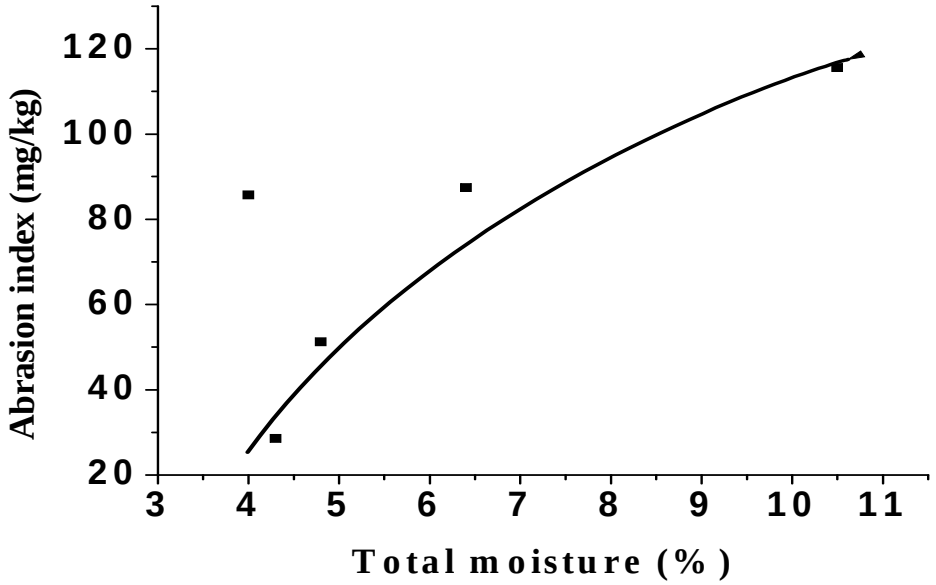


Figure 10: Effects of total moisture on abrasion index of coals

Figure 10 suggests that AI increase logarithmically with increasing total moisture. Coal D appears to be an outlier. One might argue that the resulting AI of this coal sample is not purely controlled by moisture; therefore other coal constituents need to be considered. Spero (1990) using three sets of coals concluded a linear and exponential increase respectively between AI and total moisture. Following on Coldham (1989), Spero *et al (1991*) and considering the behaviour portrait by Figure 10, it is evident that abrasion to some extended is affected by moisture.

One intriguing observation made during grinding in the AI tester pot was the temperatures that resulted due to friction. Both initial and final temperatures of the coal samples were recorded (see Appendix A, Table A3). Initial temperatures were recorded to be equal to the room temperature. The final temperatures ranged between 55°C and 65°C. These resulting temperatures led to moisture being released from the coal during grinding (Mclntosh, 1976; Morgan *et al*, 1986). This is true since the walls and lid of the grinding machine were wet at the end of every grinding process.

4.6. Hardgrove Grindability Index

Hardgrove Grindability Index is an index used to indicate how difficult coals are togrinding. The high HGI value indicates softness of coals, and a low HGI value is indicative of hard coal (Terchick *et al*, 1963). The ranges of HGI values and their meaning are given in the study by Tichanek (2008). From the latter study it is explained that any coal with HGI ranging between 40 and 60 is hard. HGI values greater than 60 (≥ 60) means a soft coal or medium hard coal. Typically, coals of the Witbank coalfield possess HGI values ranging between 40 and 66 (Falcon and Falcon, 1987). Table 5 reports both AI and HGI values of the coal samples obtained using the abrasion index tester pot and Hardgrove machine respectively.

Table 5: Grinding properties of coal

Coal name	AI (mg/kg)	HGI
Coal A	87.35	61
Coal B	115.58	50
Coal C	28.63	51
Coal D	85.70	52
Coal E	51.15	50

The results in Table 5 suggest that Coal A was soft (HGI>60); implying it ground with ease, and can be utilised for power generation (Tichanek, 2008). Four other coals are equally hard. Table 5 suggest that Coal A is both soft and abrasive. Coal B and Coal D are hard and abrasive; Coal B is most abrasive, and Coal E is hard and medium abrasive. Coal C is hard and not abrasive. A general trend acceptable between AI and HGI would be that a coal should be both hard and

abrasive. Coal B and Coal D are in support of the general statement, while Coal C and Coal A are contradictive to the general statements. Falcon and Falcon (1987) have addressed these anomalies. What can only be said is: these behaviours are known to exist with Southern African coals (Falcon and Falcon, 1987). In short Table 5 suggests that coals can be hard and abrasive, hard and not abrasive, or soft and abrasive.

In 1996 Sciezska analysed similar coals as used in this study. Scieszka (1996) reported AI and HGI of the coals to be 67.2 and 68.2 and 54.0 and 77.1. It is evident from Sciezska's results and the results in Table 5 that coals can be soft with medium abrasion, and soft and abrasive. Spero (1990) using coals from Australia, which can be compared to typical South African coals, found the same trend of HGI values as reported by this study. Spero (1990) also showed that grindability, like moisture, is equally important in establishing abrasion of coals. AI and HGI correlation is given by Figure 11.

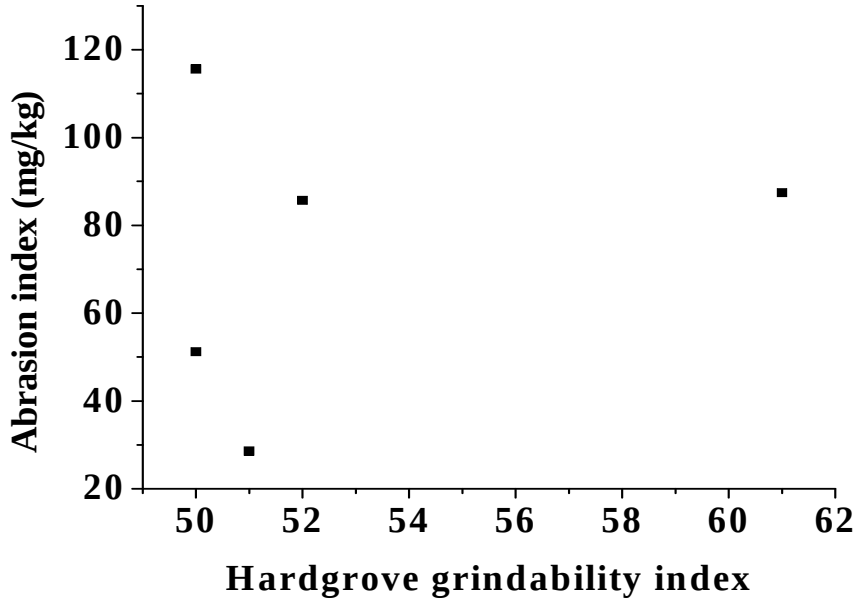


Figure 11: Correlation between AI and HGI

Figure 11 illustrates an experimental correlation between AI and HGI; no significant mathematical behaviour between these two indices is evident. This is because points on the

graph are scattered. The scattered points might suggest that the two indices are independent of each other. As AI values increase HGI values remain fairly consistent within the same range, except for Coal A. This observation makes it hard to establish any distinct relationship between AI and HGI. Terchick *et al* (1963) found the same results using Pittsburgh coals.

It can be concluded from both Table 5 and Figure 11 that AI and HGI empirical correlations might behave outside what is seen with experimental results. This means, these two indices must be tested separately when a coal sample is tested for its grinding properties. It can also be concluded that these indices are affected by different properties of coals; therefore they will measure different properties of coal samples under investigation. This may be supported by the fact that AI as described by Scieszka (1985) does not depend only on HGI, but also depends on the tribological properties of grinding system (see Chapter 1). These tribological properties include resistance of grinding elements to wear and friction which are not properties of the coal samples itself.

To further establish the relationship between AI and HGI, the factors that influence them individually according to Falcon and Falcon (1987) are highlighted. Falcon and Falcon (1987) concluded that abrasion is mostly affected by high contents of mineral matter, the presence of hard minerals such as quartz and pyrite, the nature of the minerals, types of associated microlithotypes and large coal particles. Meintjes (1965) concluded that ash content can affect AI (particularly when soft mineral like clays make-up the most of the the ash-forming minerals). Grindability of coals is controlled by inherent moisture, rank and organic compositions of coals and the grinding temperatures. Both indices are affected by coal rank, mineral composition, size and shape. In the following sections AI is related to some of these coal constituents.

4.7. Petrographic components and impacts on AI

Minerals, and mineral distribution and their association may have the greatest influence on the abrasiveness quality of coals. Petrography is a microscopic technique capable of giving such information. For this research, Leica DM4500P petrography microscope with a magnification of 500 under oil immersion with polarised light was used for maceral and rank analyses, mineral distribution and microlithotypes analysis following ISO 7404-3 (1994), ISO 7404-4 (1994) and ISO 7404-5 (1994) respectively. The abnormal conditions of the coal samples (CAC) were also investigated. Obtained results are given below, which are discussed together with the AI values of the coal samples.

4.7.1. Macerals and vitrinite reflectance

Macerals, also known as coal organic constituents, can be grouped into three groups, namely: vitrinite, liptinite and inertinite. Of the three macerals groups, inertinite, then vitrinite possess the greatest hardness (Falcon and Falcon, 1987). The strength of inertinite is mostly controlled by its dense character. Its abrasiveness is strengthened when it is in association with hard minerals like quartz (Falcon and Falcon, 1987). The abrasive properties of inertinite and vitrinite macerals have not been confirmed independently. Liptinite is known to be soft. Table 6 represents the maceral groups, %, total mineral matter (MM, %), and reflectance of vitrinite, % of the coal samples. Full set of results are reported in Appendix A, A.2.2, Tables A4-A9.

It can be seen From Table 6 that all coals comprised mainly of inertinite macerals, typically being inertodetrinite, low to moderate vitrinite and liptinite macerals. These values are typical of Witbank Coalfield ROM coals (Falcon, 1989). High proportions of mineral matter are reported for Coal D and low values for Coal C. Coals D and E have low CAC values when compared to the rest of the coals. Results in Table 6 and Figure 12 may infer that Coal C is oxidised. Any coal that is oxidised is friable. Friable coals are identified with these characteristics: macro-porous, uncompacted semi-fusinite and fusinite, cracking and minor fissuring (Falcon and Falcon, 1985). Coal C was highly discoloured; was the only coal with intense cracks, prominent fissures and highly leached (see Table A8, Appendix A and Figure 12).

Table 6: Summary of macerals, reflectance of vitrinite and CAC

	AI	Maceral, Vol %				Rank (RoVmr)	CAC
Coal name	**(mg/kg)**	**Vitrinite**	**Liptinite**	**Inertinite**	**MM**	**Vol%**	**Vol %**
Coal A	87.35	15.2	4.8	63.2	16.8	0.63	32.4
Coal B	115.58	31.0	4.4	43.8	20.8	0.62	31.2
Coal C	28.63	7.0	5.0	74.4	13.6	0.73	32.2
Coal D	85.70	9.4	2.8	57.0	30.8	0.70	20.0
Coal E	51.15	14.2	1.6	64.2	20.0	0.72	19.7

MM=mineral matter, CAC=coal abnormal conditions and RoVmr= Reflectance of vitrinite maceral.

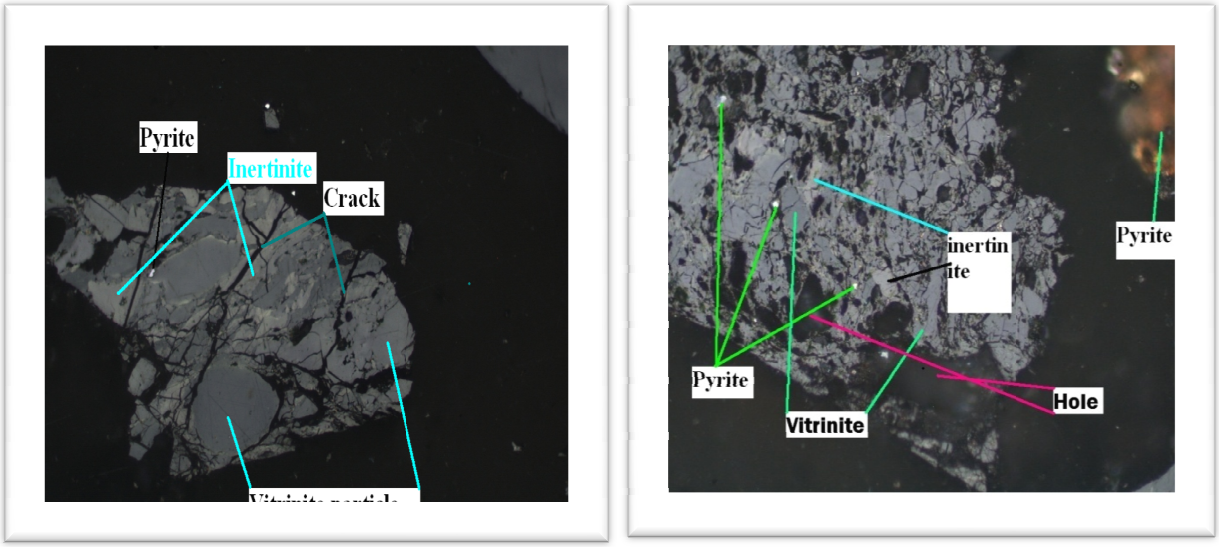
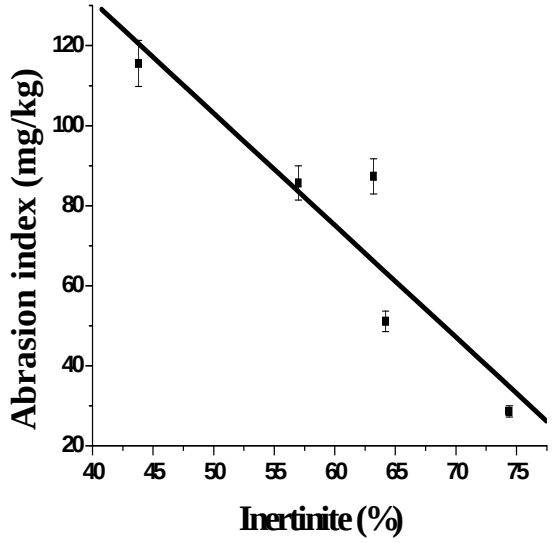


Figure 12: Micrographs of Coal C (fresh and oxidised coal particles)

Figure 12 represent the micrographs of Coal C taken using petrography microscope. The micrograph on the left presents a fresh coal whilst the one on the right is indicative of an oxidised coal particle. The redish-brown colour on the micrograph on the right is an oxidised pyrite mineral. It appears that only Coal C displayed some degree of heat effects. Using petrographic microscope, Coal C was not effectively shown to be weathered, but realising that this coal had intense cracks, intense fissures, was discoloured, possibly rich in inert semi-fusinite, highly leached, all this can infer that this coal was friable. It might be due to friability or CAC that this Coal was not abrasive. The recommendation on the CAC of Coal C is that this analysis needed to be carried out on particle size of +850-1475 µm instead of -1000 µm.

Reflectance (RoVmr %) analyses were also conducted on the coal samples. Reflectance of vitrinite is used to infer the rank of coals; this was done following on ISO 7404-5 (1994). Results show that the selected coals are medium rank C coals (Appendix A, Table A6). From Table 6 it can be said that Coal B had highest proportions of vitrinite, lowest inertinite and it was the most abrasive. Coal C had high inertinite, least vitrinite and was not abrasive. Coals A and D have equivalent amounts of both inertinite and vitrinite and are equivalently abrasive. A general conclusion drawn from Table 6 is: any coal with high vitrinite and low inertinite appears to be abrasive. In addition Table 6 indicates that equal proportions of both vitrinite and inertinite (together) can lead to an abrasive coal. Figures 13 and 14 were generated from results in Table 6.



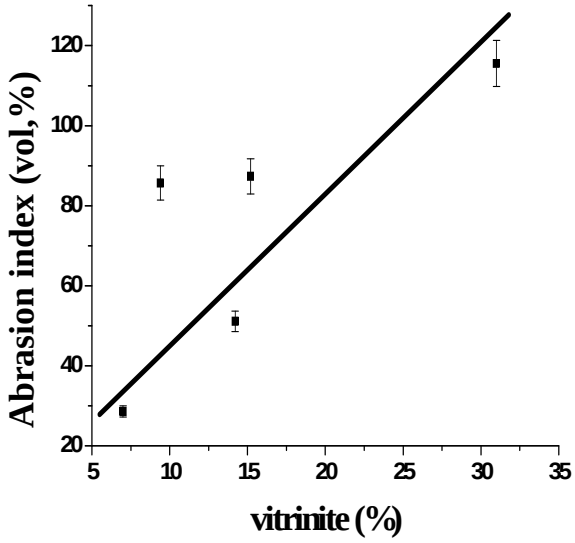


Figure 13: Influence of inertinite and on AI

Figure 14: Influence of vitrinite on AI

Figure 13 illustrates the effects of the inertinite on abrasion. It appears that a decrease in inertinite macerals results in an increase in AI value (R^2=-0.92 and SD = 14.89). This might be true realising the fact that, even though inertinite is hard, its effects on coal's abrasion are prominent only when it is in association with high portions of hard minerals such as quartz.

Figure 14 illustrates the effects of vitrinite on abrasion of coal samples. It is evident from Figure 14 that an increase in vitrinite content causes an increase in AI values (R^2=0.78 and SD=24.95). Both figures give positive results. A probable explanation for the relationship given by both figures may be linked to residence time of grinding (Mclntosh, 1976; Stamboliadis, 2007). Vitrinite, which is sticky, can stick to grinding elements for longer period, unlike inertinite which is dry and can quickly pulverise thereby not imposing severe wear.

In summary it is evident that the reported AI values were influenced greatly by vitrinite as oppose to inertinite. Also, oxidised or friable coals will not be abrasive. That is, oxidised condition of coals override abrasion in coals.

4.7.2. Minerals determined using petrography microscope

High mineral matter content and hard minerals like quartz and pyrite are reported to contribute to the abrasive quality of coals (Raask, 1985; Wells *et al*, 2004, 2005; Wigley and Williamson, 2005). Quartz was established to be twice as abrasive as pyrite by Raask (1985). Minerals such as alumina, orthoclass, kyanite and topaz, and other hard minerals can cause coals to be abrasive, but their effect is low when compared to quartz and pyrite (Wigley and Williamson, 2005). This is because in general quartz in coals exists in isolation (Wells *et al*, 2005). Carbonates, clays, sulphates and phosphates minerals are known to be soft, and hence they do not contribute to the abrasive quality of coals. The influence of soft minerals on abrasion is magnified only when they occur together with inertinite macerals, which is the hardest of all macerals (Falcon and Falcon, 1987). Table 7 shows the petrographically determined minerals in the coal samples, reported in volume %.

Table 7: Petrographically determined minerals

Coal name	AI (mg/kg)	Clays vol%	Quartz vol %	Pyrite vol %	Carbonates vol %	Other minerals vol %	No VM vol%
Coal A	87.35	79.6	7.8	5.2	5.6	0.8	1.0
Coal B	115.58	84.6	3.6	3.2	4.4	0.4	3.8
Coal C	28.63	86.8	4.4	1.4	5.6	1.0	0.8
Coal D	85.70	74.8	6.4	1.2	0.6	0.8	16.2
Coal E	51.15	44.2	35	3.8	5.2	0.4	11.4

Note: No VM means no visible minerals

Clay, quartz, pyrite and carbonates constitute the total mineral matter in the coal samples. Total mineral matter (% MM) is reported in Table 6. Coal D appears to have the highest total mineral matter; Coal C had the least total mineral matter. In general these coals had significant total mineral matter, except probably for Coal C, which had total mineral matter less than 14%. This is not surprising since it was thought possible that this coal might have been oxidised (Table 6) and had most ash content (Table 1).

Table 7 reports significant amounts of clay minerals for Coals B and C; followed byCoals A and D, then Coal E. In contrast Coal E has the most proportions of quartz, followed by Coals A and D, lowest in Coal B and C. Coal A has significant proportions of pyrite. Pyrite in other coals occurred under less that 5%. Carbonate minerals were present in all coals except for Coal D. In Table 7, other minerals refer to unknown minerals. Figure 15 illustrates how minerals (as determined petrographically) in the coal samples influenced AI.

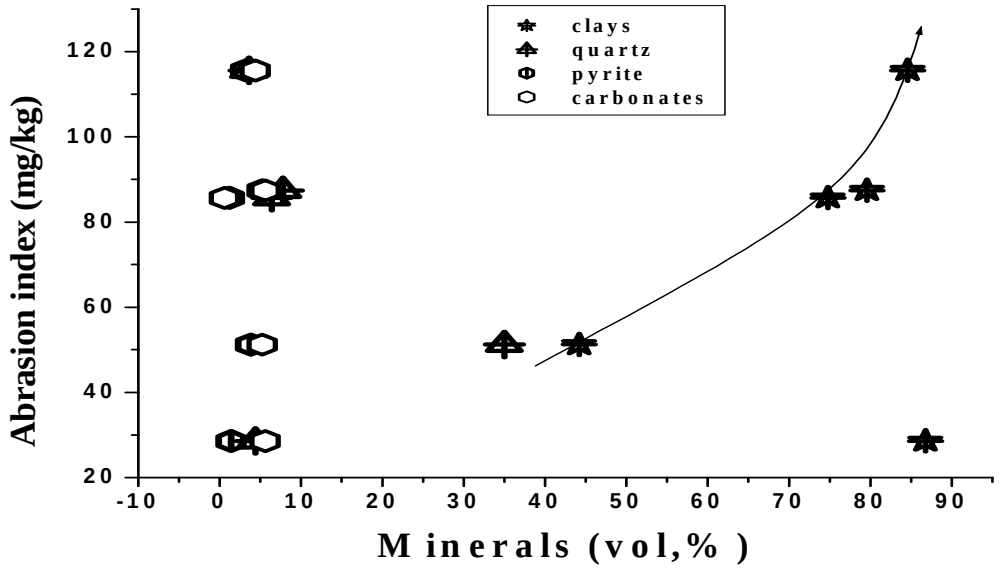


Figure 15: Effects of different mineral on abrasion index

Different symbols as shown on Figure 15 are used to indicate different group of minerals. From Figure 15, it appears that AI is influenced by clay minerals, which gave an exponential increase

with AI. Coal C is an outlier on a drawn correlation between clays and AI; this might be due to its oxidised nature or CAC (Table 6) which will always results inhigh proportions of clay minerals being reported for a coal. It is apparent from Figure 15 that quartz; pyrite and carbonate minerals equally did not affect AI. Coal E appears to have high portions of quartz hence it is an outlier, but its AI value was not that high compared to the other coals, this shows that AI of the coal samples was not influenced by quartz. Abrasion was not affected by the said minerals as Figure 15 concludes that AI was independent of these minerals. The observation that clay minerals are most contributing to abrasive quality of coals can be due to the fact that these minerals, unlike pyrite, are concentrated in South African coals. Separately, correlation between silicate minerals, which is a combination of both clays and quartz, and AI was drawn. A linear relationship with R^2= 0.6 was obtained (Appendix A, Figure A6).

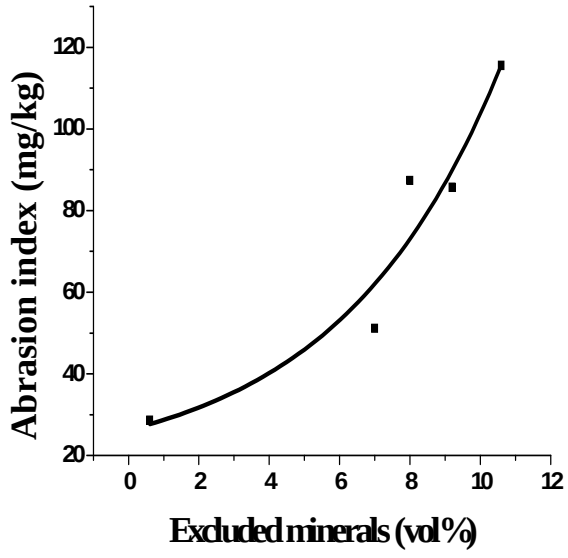
In summary, Figure 15 together with Table 7 reveals that only clay minerals appear to contribute to the overall AI since their effects seems to be an exponential correlation. Quartz and pyrite were not abrasive as was anticipated. This observation is supported by Coal E which had high amounts of quartz and some pyrite contents of all coals, but had the lowest AI value; this is if Coal C is taken to be not abrasive, owing to the inconclusive analogy that it might be oxidised.

Excluded minerals in coals were also used to establish effects of minerals on abrasion. Petrographically, excluded minerals are reported as rocks during microlithotypes analysis. By definition excluded minerals refers to minerals in coals which are not bound within the coal macerals. Results on %, total mineral matter and %, excluded mineral matter are given in Table 8.

Table 8: Data on excluded minerals and total mineral matter

Coal name	AI (mg/kg)	Excluded minerals % from microlithotypes	Total carbominerite from microlithotype analysis	Total mineral matter % from macerals group
Coal A	87.35	8.0	10.0	16.8
Coal B	115.58	10.6	12.0	20.8
Coal C	28.63	0.6	5.8	13.6
Coal D	85.70	9.2	20.2	30.8
Coal E	51.15	7.0	10.0	20.0

Table 8 seem to suggest that excluded minerals appear highest in Coal B followed by Coal D and Coal A respectively. The least excluded minerals are reported for Coal C. Coal B was most abrasive followed by Coals A and D, and then Coal E. Coal C was not abrasive. This observation corroborates the fact that excluded minerals influence abrasion of coals. Coal D compared to Coal B was less abrasive but had the highest value for total mineral matter. Total mineral matter is the sum of excluded and included minerals. Also noticeable is that Coals A and D have comparable AI value, but the total mineral matter is reported much higher for Coal D (double). These observations are ascertained by Figure 16 and Figure 17, which plot AI value against the corresponding excluded mineral and total mineral matter. Carbominerite reported above are discussed in the next section.



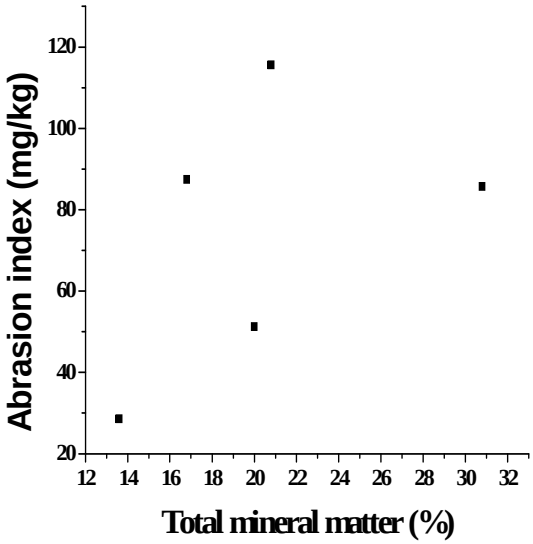


Figure 16: Effects of exclude minerals on AI

Figure 17: Effects of total mineral matter on AI

Figure 16 significantly shows that AI increases exponentially with excluded minerals. Figure 17 reveals that abrasion increases with increase in total minerals. In short it is evident from Table 8 and Figure 16 that abrasion of coal samples increases exponentially with excluded minerals. High total mineral matter can cause coals to be abrasive, unless if that coal is oxidised (as in Coal C).

4.7.3. Microlithotypes

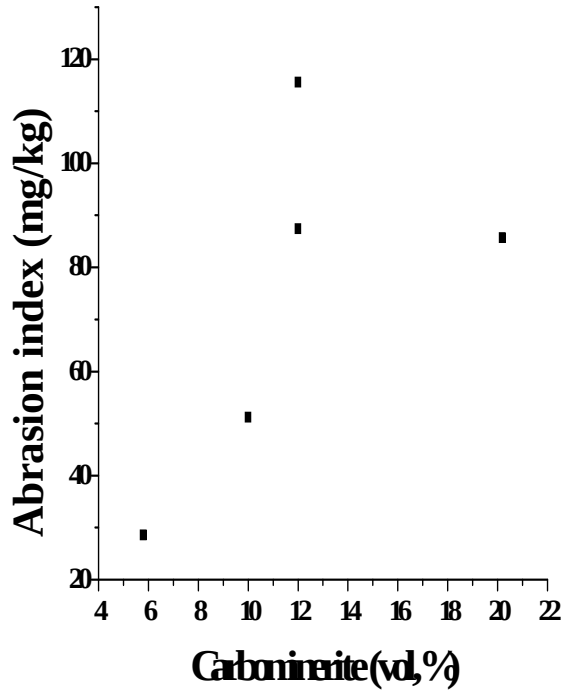
The microscopic layers that form from the association of both organic and inorganic components of coal, occurring in width greater than 50 µm, are termed microlithotypes (Falcon and Snyman, 1986). The microlithotypes groups discussed here were analysed following ISO 7404-4 (1994), reported in volume %. The full set of results on the microlithotypes analysis is located in Appendix A (Table A5). Table 9 reports a summary of the analysed microlithotypes with the AI values.

Table 9: Abrasion index and Microlithotypes

Coal name	AI (mg/kg)	Carbominerite Vol %	Vitrite Vol %	Inertite Vol %	Intermediates Vol %
Coal A	87.35	10.0	9.6	35.2	11.8
Coal B	115.58	12.0	23.8	18.0	9.6
Coal C	28.63	5.8	4.0	33.4	9.4
Coal D	85.70	20.2	8.0	14.0	8.6
Coal E	51.15	10.0	9.6	35.2	11.8

Note: intermediates refer to bi and tri- microlithotypes.

The effects of these microlithotypes are shown below, but, with the exclusion of organic microlithotypes or mineral free microlithotypes. From Table 9 it is evident that AI increases with vitrite, and decreases with inertite.



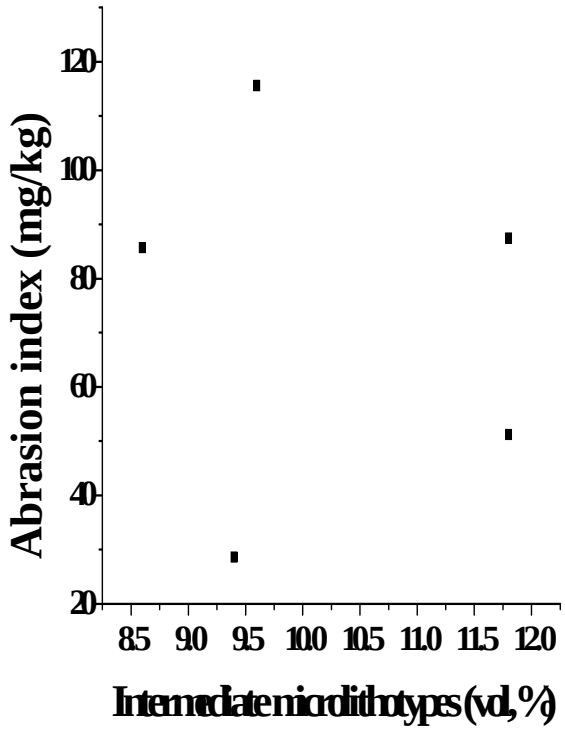


Figure 18: Effects of carbominerites on AI **Figure 19: Effects of intermediate microlithotypes on AI**

Figure 18 shows that there is a clear correlation between AI and carbominerite. An exponential behavior is portrait by Figure 18, which suggests that carbominerite did impact on the abrasive quality of coal samples used for this study. However, there is an outlier (Coal D) which makes it impossible to conclude with efficacy that carbominerite are influential to AI in this study. In contrast to literature, no conclusive deductions could be made from Figure 19, which shows a lack of correlation between intermediates microlithotypes to AI. This is not in support of the literature that concluded that, bi macerals and in particular tri macerals are hard enough to induce abrasive quality of coals.

To summarise, section 4.7, this section shows the effects of vitrinite and inertinite on AI in section 4.7.1 and Table 9. It is shown here that vitrinite did influence the AI as oppose to inertinite which increased with a decrease in AI. In section 4.7.2 it was shown that silicates in the coal samples impacted on the reported AI values, but pyrite and carbonate minerals did not

impact on the reported AI values. This is shown by Figure A5 in Appendix A and Figure 15 respectively. This section also shows that carbominerite might have influenced the reported AI, and excluded minerals, not intermediates microlithotypes did not influence AI as well as total minerals.

4.8. Chemical analyses

X-ray fluorescence was used here to determine the ash oxides of coal samples. X-ray diffraction was used for mineral quantification using Rietveld analysis. SEM-EDS was used to characterise the shape and the morphology of coal particles. The chemical constituents of the coal samples determined with SEM-EDS are given in Appendix A, Table A10-A14. Results obtained using these techniques are given below together with their discussion.

4.8.1. X-ray fluorescence spectroscopy

The ash oxides reported in Table 10 were determined from Wit-lab. What is significant from the results reported in Table 10 is that the coal samples analysed show a different range of the chemical composition. Note that Cr_2O_3 is not reported in Table 10 as it was obtained to be 0.01% for four coals and 0.04% for Coal C.

The results in Table 10 show that SiO_2 for all coals samples was at least 50% and higher. Low and high SiO_2 is reported for Coal E and Coal B respectively. Similarly Al_2O_3 is reported between 23% and 35% for the coal samples. Coal D has at least 33.49% Al_2O_3, and Coal B had 23.09% of Al_2O_3 which was the lowest. As anticipated oxides such as CaO, MgO, TiO_2, and Fe_2O_3 are significant, but in relatively small quantities for all coal samples. The exception is Coal C, reports relatively high content of Fe_2O_3. Iron oxide is an oxidised form of pyrite. Low sulphur is reported for Coal D only.

Table 10: XRF Constituent Analyses: Air dry base, %

Coal name	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5	CaO	K_2O	MgO	Na_2S	MnO	SO_3
Coal A	56.13	24.54	6.27	4.60	0.16	2.53	0.36	1.05	0.28	0.02	2.44
Coal B	57.41	23.09	5.29	4.70	0.20	2.70	0.48	1.13	0.31	0.02	2.60
Coal C	50.08	25.83	10.01	4.60	1.11	2.61	0.39	1.33	0.09	0.05	1.60
Coal D	54.46	33.49	2.62	5.03	0.46	0.74	0.27	0.37	0.07	0.01	0.44
Coal E	49.02	29.26	6.17	4.19	0.70	3.38	0.32	0.93	0.07	0.03	2.76

Looking at Table 1 and Table 10, it can be suggested that the reported ash values in Table1 were made up mostly of SiO_2 and Al_2O_3, then MgO, SO_3,CaO, Fe_2O_3 and TiO_2 and least mounts of Na_2S, MnO, K_2O and P_2O_5.

4.8.2. X-ray diffraction

X-ray diffraction is one of the first techniques to be able to definitively identify minerals in coal samples. The use of Rietveld methods has advanced the determination of minerals in coals. It is emphasised that when reporting XRD data the errors must be reported as the minerals determined using XRD are semi-quantitative owing to its limitations (Ward, 2002). XRD patterns of the identified phases of the minerals are reported in Appendix A, Section A.2.3. The results in Table 11 were determined using PAN alytical X'Pert Pro powder diffractometer with X'Celerator detector and variable divergence- and fixed receiving slits with Fe filtered Co-Kα radiation.

Table 11: Mineralogy of coal samples (ROM) using SIROQUANT (wt, %)

Mineral	Coal A	Coal B	Coal C	Coal D	Coal E
Anatase	0.65	0.95	0.66	1.06	0.58
Ankerite	3.72	1.42	0.42	3.64	4.23
Calcite	2.37	1.35	0.00	3.86	2.68
Dolomite	0.89	1.31	0.18	0.63	0.18
Graphite	57.30	45.40	57.45	37.9	53.50
Gypsum	0.00	0.00	0.00	0.00	0.69
Kaolinite	20.49	28.88	31.37	33.75	26.60
Magnetite	0.81	1.12	0.71	1.29	0.87
Pyrite	1.32	1.13	0.88	0.52	1.57
Quartz	12.10	18.02	7.78	14.25	7.23
Rutile	0.38	0.38	0.39	0.49	0.23
Siderite	0.00	0.00	0.16	2.60	1.58

Table 11 shows the principal minerals that were present in the coal samples using XRD.

Reported results indicate that all coal samples contained significant amounts of kaolinite (clay mineral), quartz (silicon dioxide mineral) and ankerite (carbonate mineral). Also present in the coal samples was calcite (carbonate mineral) except in Coal C which reported 0.00% calcite. Rutile, pyrite, magnetite, anatase, and dolomite are minor minerals reported for the coal samples. Siderite was a minor mineral in Coals C, D, and E, and was absent in Coals A and B. Siderite is an iron-bearing mineral like pyrite and magnetite. Gypsum was not reported for all four coals but it was present in Coal E in minor quantities. Graphite which is a semi-quantification of all the organic carbon (as well as other amorphous phases if present) represented all the amorphous phase materials that were present in coals.

In general results in Table 11 indicate that the coal samples contained mostly of clay mineral followed by quartz mineral then carbonate minerals. Iron bearing mineral particularly siderite and pyrite were minor mineral present in the coal samples.As discussed in Chapter 2, certain minerals are responsible for the abrasive quality of coals. Minerals such as quartz and pyrite have a great influence on AI. Carbonates are soft and least abrasive. To indicate what Table 11 means to this study, mineral grouping were used to investigate which mineral group influence AI. Figure 20 was generated from the results in Table 11.

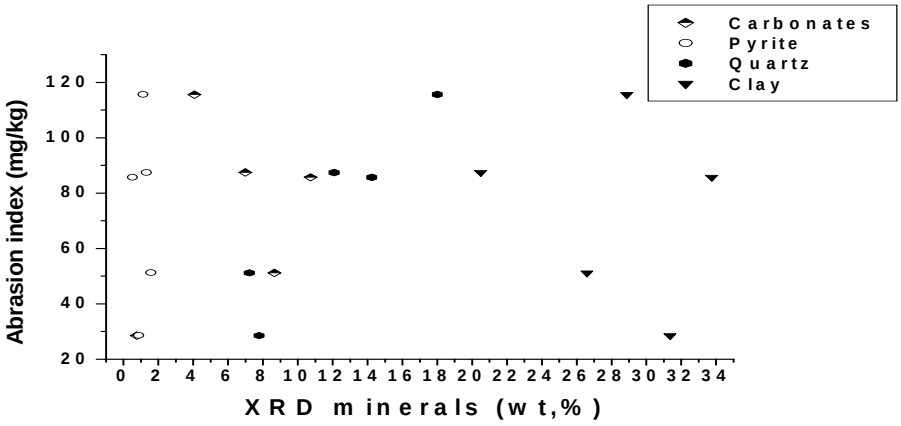


Figure 20: Effects of principle minerals on AI

Figure 20 suggests that quartz certainly influences the abrasive quality of coal samples. This is because AI increases linearly with increasing quartz content. There appears to be an outlier in the

correlation drawn between quartz and AI. This outlier is Coal C. A general trend exists between AI and clay minerals. Figure 20 suggests that when clay minerals increase, AI decreased. But this was not conclusive as only three coals are in agreement with the statement and two other coals which are Coals D and E did not conform to the observation. Figure 20 suggests that carbonate minerals increased linearly with decrease in AI. Least amounts of carbonate minerals were reported for Coal C which was an outlier in a correlation drawn between carbonates and AI. It appears from Figure 20 that pyrite was not influential tothe reported AI values. This is true since pyrite in South African coals is least disseminated compared to other minerals like clays, and it exists in association, unlike quartz which are present in isolation in coals.

This study looked at both ash analysis (TGA and XRF), mineralogy by both XRD and petrography, it is therefore necessary that the results should be compared. For comparison reasons total minerals (Table 8) as determined by petrography and XRD are used, and also XRD results are compared to the ash analysis reported in Table 1. These results are combined and are shown in Table 12.

Table 12: Comparison between XRD, Ash and Petrography

Coal name	XRD mineral	Ash by TGA	Petrography mineral
Coal A	42.73	30.7	16.8
Coal B	54.56	38.6	20.8
Coal C	42.55	41.2	13.6
Coal D	62.09	42.0	30.8
Coal E	46.44	33.6	20.0

Note that in Table 12, the given XRD results are only minerals; exclusion of graphite results, and the reported Petrography minerals are total minerals from the macerals group.

Generally speaking it is known that petrographically reported minerals are always less than the XRD determined minerals. The difference can be attributed to the known fact that petrography is a point count microscope; therefore its ability to quantify minerals in coals can be influenced by particle size, which is not a problem with XRD techniques. Also ash, which is the remains of burnt coals, has to be less than the actual reported XRD minerals (Hutton and Mandile, 1996). Comparison, by inspection following on Table 12, between XRD determined minerals and petrography is somehow what was anticipated. The difference is attributable to PSD analysed. Petrography reports at least 20% of minerals for Coals B and E, and XRD reports a difference of 8% for the said coals. Similarly petrography reports 2% difference of minerals between Coals A and C while XRD reports 42% difference.

Comparison between ash and XRD is also given in Table12. What is obvious in the table is that ash is less than XRD reported minerals. This statement is supported by all coals except Coal C. At least 1.4% difference between XRD minerals and ash is observable. The reasons as to why the ash content and mineralogy quantified using XRD is equally for Coal C cannot be accounted for, but it can be suggested that the said coal might had suffered in-situ oxidation which can lead to mineral transformation. It is a known fact that minerals such as carbonates, and kaolinite can dehydrate. Kaolinite can be influenced by low temperature hydrothermal alteration thereby reporting high aluminium silicate; which is the primary ash forming constituent together with silicon dioxide (Matjie and van Alphen, 2008). XRF and XRD report at least 34% of aluminium silicate and kaolinite respectively for Coal D and 2% difference of the said constituents for Coal E. But, in the same sequence these techniques reports 4%, 5%, and 6% difference of the said constituents for Coals A, C and B respectively.

The other thing prominent between XRD and XRF reported data is the iron content, which in XRD is reported as hematite, pyrite and siderite, and for XRF is reported as iron oxide (Fe2O3). Low contents of iron bearing minerals are reported by XRD, but XRF has reported an enormous increase in iron, particularly for Coal C which has at least 2% of iron bearing minerals, and had reported 10% of iron oxides. What can be said looking at XRF and XRD data is that the disparity

in the results is transparent, the differences which cannot be accounted for, the only thing that can be said is that, it must be realised that XRF is an elemental technique and XRD is a quantification technique. The results produced by these techniques can be influenced by both the analytical procedures for analysis and also the preparation methods.

In summary, this study made the observation that quartz affects the abrasive quality of coals as reported by XRD. Carbonates and clays did not lead to coals being abrasive. Abrasion of the coal samples was not influenced by pyrite as anticipated. Minerals determined using petrography and XRD concluded different effects to AI. Petrographic analysis indicated that only clays did affect AI of coals. XRD analysis concluded that quartz are highly abrasive, and that the abrasive quality of coals decreases with increase in clays and carbonates. Equally though, these techniques showed that pyrite in South African ROM coals is not abrasive. TGA results and XRD reports ambiguous results for Coal C only. The difference in results reported by both XRD and XRF can be attributed to sample preparation and methods of analysis (analytical errors).

4.8.3. Energy dispersive scanning electron microscope

Coal samples were analysed for their shape and morphology using SEM technique. Digital back scattered images were captured at 500 magnification, randomly across the coal sample surface area. Using energy dispersive X-ray spectrometer (EDS), the chemical analyses of the samples were obtained. They are included in Appendix A, A.2.4, as they were used to compare with the XRF results obtained from Witlab. Results were obtained, which were interpreted based on the shape, size and morphology. Figure 20 shows the morphology of the coal samples. It is well established that sharp coal particle together with minerals are far abrasive than round particles; this is due to indentation effects. Non round particles are able to indent on any metal surface they come into contact with. Discussion on these micrographs will be used in connection with the reported AI values to illustrate the effects of morphology on wear.

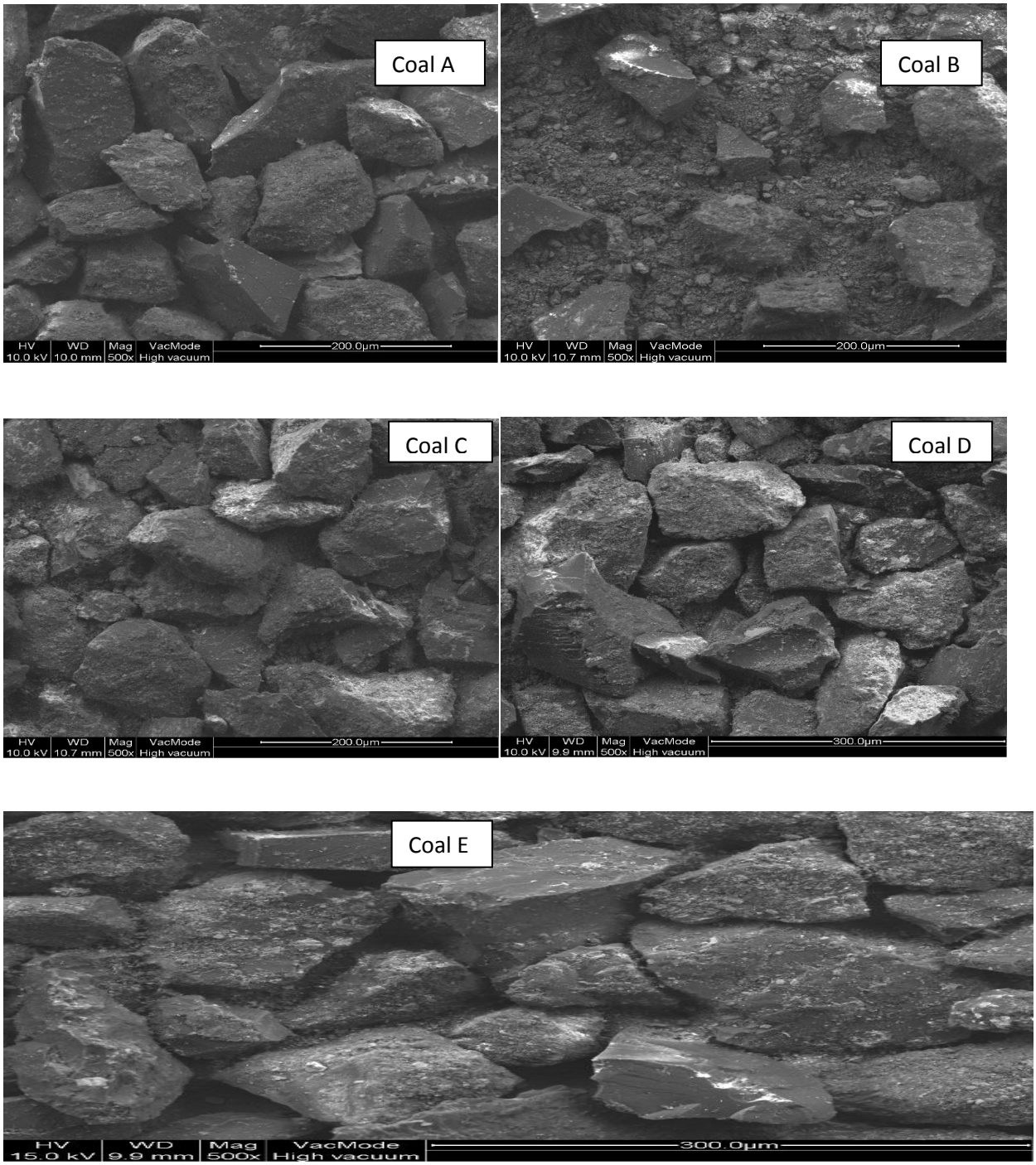


Figure 21: SEM micrographs of the coal samples (Coals A-E)

The micrographs of Coal A aboveshows that this coal had mixed particles. The mixture is comprised of particles that are laminar with almost blunt edges, and round edge particles. The micrograph of Coal B micrograph shows that this coal had fine grains mixed with very edged

and sharp particles. No round particles are observed within this coal sample. Coal C micrograph indicates that this coal had predominantly round, least edged, non sharp particles, which appeared to be enclosed by round particles. Coal D micrograph indicates that this coal sample had particles that were not round, edged, but blunt particles. Coal E had particles that were round with edges, and laminar. Described morphologies of all coal samples may indicate that Coal B is likely to be abrasive, Coal C unlikely to be abrasive at all, Coal E may be a medium hard or abrasive coal, with Coal A and D being almost equally abrasive. The AI values reported in Table 3 follow a similar trend.

From both Table 3 and the micrographs of the particles discussed above, it may be distinct why Coal B is the most abrasive of all coals studied, and why Coal C is not abrasive. It may also be noticeable why Coals A and D are equally abrasive.

4.9. Particle size distribution

Particle size analysis (PSD) was conducted on the product coals, after the abrasive quality of coal samples were tested, using a sieve method. PSD results are given in Table 13. Four class sizes were decided on as indicated in Table 13. It is clear that only 19% of Coal B feed material (2000 g) passed the target sieve (- 75 µm), which is the least, followed by Coal A, where only 30.25% passed the target sieve. The most material recovered passing the target sieve is for Coals D, C and E, which are 34.75%, 34.5 % and 32.5%, respectively.

The top sizes indicate that out of the total material fed into the abrasive tester pot for grinding 59.25% of Coal B and 56.75% of Coal A did not reduce. The coals that had most of the feed material (-1475 µm) reduced are Coals C and E. Of Coal D feed material, only 47.75% passed the top size mesh. These results indicated that Coal B was most resistive to grinding, followed by Coal A and D, then Coal C and E. From this is possible to conclude that Coal B was most abrasive followed by Coals A and D, the least abrasive were Coals C and E. Table 3 similarly reports the same trend of abrasiveness of the coal samples.

Table 13: Particle size distribution obtained using sieve method after AI testing

Coal Name	AI (mg/kg)	Class 1 -75 µm	Class 2 +75 –150 µm	Class 3 -150 +850 µm	Class 4 -850+1470 µm
Coal A	87.35	605.00	30.00	135.00	1135.00
Coal B	115.58	380.00	70.00	270.00	1185.00
Coal C	28.63	690.00	50.00	205.00	1030.00
Coal D	85.70	695.00	45.00	200.00	1045.00
Coal E	51.15	650.00	50.00	220.00	1030.00

PSD reported in Table 13 are indicative of the resistivity of coals to grinding. PSD analyses can be related to wear. Yancey, Geer and Price cited in Spero (1990) concluded that the greatest abrasion sustained by blades is generally caused by coarse particles. Spero (1990) concluded that a coal that grinds with ease is quickly reduced to the finer sizes and exhibits less abrasion, while a hard coal is not easily and rapidly pulverised, hence becoming abrasive over a longer period of time. The PSD analyses conducted herein may be in support ofthe said statements.

Figure 22 illustrates the effects of PSD on AI. Class 1, Class 2, Class 3 and Class 4 are indicative of PSD (-75 µm), (-150+75 µm), (-850+150 µm), and (+850-1475µm) respectively. These classes of PSD are indicated in Table 13. The middle class (class 2 and class 3) seem to have no effects on the reported AI of the coal samples. R^2 values of 0.067 and 0.043 were obtained. Figure 22 supports the observation that coarse particles are abrasive. This is indicated by Class 4 on the figure, which has R^2 of 0.705. Class 1, which is represented by PSD less that 75 µm mesh, decreased with an increase in AI. That is, abrasion decreases with increasing mass recovered for

Class 1. These results, both Table 13 and Figure 22 confirm that abrasion is dependable on coarse particles, and increases with decrease in mass recovered for fine coals or Class 1.

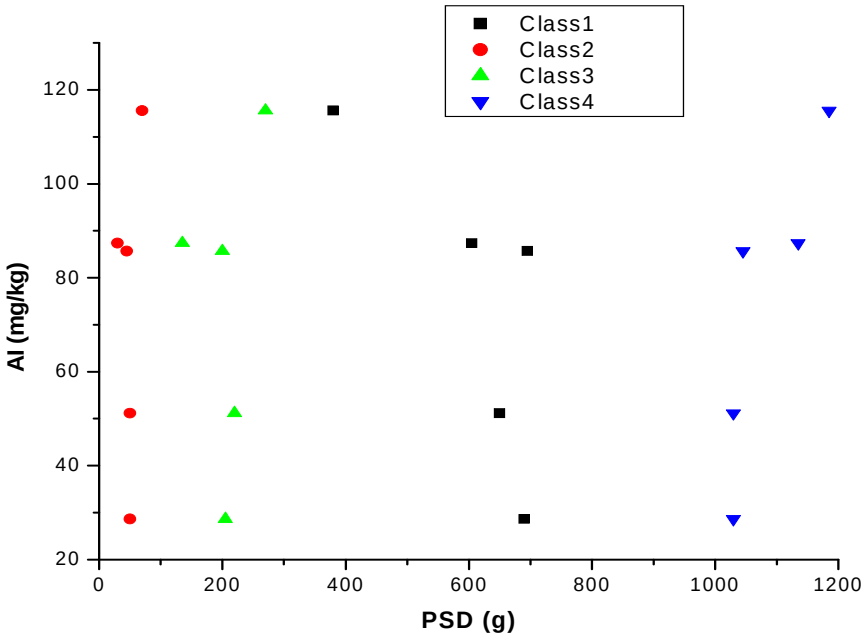


Figure 22: Effects of PSD on AI

In summary, this study has show that Coal B and Coal A, and Coal D are abrasive because of the high moisture content, high vitrinite content, low inertinite content, high content of total minerals (both included minerals and excluded minerals) including quartz, significant amounts of monomaceral (vitrite), and consisting mostly of non-round particles. The same constituents of coals that influenced the latter coals had influenced AI of Coal E. The only difference was the mineral quantities, which were variably less in Coal E. Coal C was thought to be oxidised, it therefore was not abrasive.

The results indicate that coals can be soft and abrasive or hard and not abrasive. Regression analysis produced using experimental results concluded that HGI and AI are independent. This study showed that excluded minerals and included minerals are equally abrasive. This study therefore has succeeded, using analytical techniques that were chosen, in revealing the key

characteristics of coals that lead to abrasion during grinding. Three body abrasive wear was found to be the resulting wear, when coal were ground in an abrasion index tester pot.

4.10. Abrasiveness, Grindability and Energy

If a mill is to effectively and efficiently grind coals, coals need to be dried. This is because moist coals grind with difficulty, which then results in enhancing power or energy consumption. The understanding of how much energy a mill uses to reduce feed coal of particular size to pulverised size is of importance. The importance of this is purely cost and maintenance related. An abrasion index tester pot used in this study ground coals by means of the impact mechanism, revolving at 1470 rpm for 12000 revolutions. To determine total energy utilised by the pot during grinding, equations for rotational bodies were used. The energy formula for YGP mills is given in Scieszka (1985) without derivation.

For this study the said formula was first derived then used. It was derived from first principles of rotational motions (mechanics). The nature of the mill and the blades, the revolutions the pot will complete at a particular speed to complete grinding, and the feed masses of coals are given. For the derivation of the energy equation from first principles, only the revolutions and angular speed are of importance. The derivation is given in Appendix B. Here the derivation is summarised and used.

4.10.1. Calculations using an energy-time derived formula

4.10.1. (a) Conversion factors:

$$\theta = 12000\ revs\ or\ \theta = 12000 * 2\Pi = 75398.22\ \text{rad} \quad (4)$$

$$N = 1470 \pm 30\ rpm, \omega = \frac{2\Pi}{60} = 153.94\ rad\ s^{-1} \quad (5)$$

By definition energy input is the product of torque, number of revolutions and angle of rotation;

$$E = \theta\tau \quad (6)$$

Where θ *and* τ are angle of rotation and torque respectively

$$E = R_v^2\omega^2 \quad (7)$$

Where $R_v^2 and \omega^2$ *arerotorradiusandangularvelocityrespectively*

Equation (7) is brought here to calculate the energy of the mill at full speed. That is, the energy of the mill at steady state. The formula is given in Nikolov (2002; 2004).

4.10.1. (b) Energy calculations:

To arrive at the determination of energy input, torque must be calculated. Torque is defined as the tendency force (F) to rotate an object. For rotational motion's, Newton's second law can best be used to describe the relationship between torque and acceleration. Torque is the product of mass (I) moment of inertia and the angular acceleration (α). Mathematically expressed as:

$$\tau = I\alpha \quad (8)$$

I used in this study was calculated and used as a constant. As for the determination of α rotational motion equation was considered.

Angular acceleration for rotating bodies is defined as: $\omega_f^2 = \omega_i^2 + 2\alpha\theta$ (9)

$$Where\ \omega_f^2\ and\ \omega_i^2\ are\ final\ and\ initial\ angulaur\ velocities\ respectively$$

When equation (9) is rearranged making α subject of the formula, angular acceleration is obtainable. Since the grinding component of abrasion index tester pot is stationary at first, the first term on the right hand of equation (9) is 0 rpm. This term is the initial rotational speed. By substituting the values obtained in equation (4) and (5) into equation (9), α was obtained to be 0.157 rad/s^2. Substituting this value into equation (8), torque (τ) was obtained to be 0.314 kg rad/s^2. In this study torque is calculated in order to establish how much energy is utilised when 2 kg of coal is rotated. By substituting 0.314 kg rad/s^2 into equation (6) and multiplying by

rotational angle which was taken to be 2π for a single completed revolution, E was obtained to be 1.973 Kg rad^2 $s/^2$. This is the energy used by a mill when charged. For steady state using equation (8), energy was calculated to be 148.764 kJ. The latter energy values will be used to calculate the energy a mill use at the initial stages of mill where abrasion is assumed to be very intensive.

Five ROM coals were used in this study. It was therefore important to understand how much energy was needed to grind a particular coal under standard conditions assuming the total moisture reported in Table 2. To calculate energy values for every coal, an equation relating torque to time was to be established. This torque-time equation is termed the integral torque as described in Scieszka (1985). Mathematically integral torque is expressed as:

$$\tau = \frac{1}{t}\int_0^t \tau dt \qquad (10)$$

Where τ is an average integral torque, Nm

To describe the effects of time on torque during grinding or milling, consider Figure 22and see a study by Rabinowicz *et al* (1961). Let Figure 22represent a hypothetical trajectory path depicting power consumption by a mill during comminution. A, mark the starting point or initial grinding point were power is still minimum; B, the point at which the mill has reached maximum speed (steady state); C, is a steady state region. Phase A-B shows the power consumption with an increase in time, which is exponential. At this stage it can be assumed that, the mill is not at full speed, therefore energy consumption will increase with time hence abrasion will be maximum. Phase B-C is a steady state, so to speak. Here, the mill is assumed to be at full speed. At this stage power is no longer dependent on the speed of the mill as well as time, as it is stated in Austin (2004) that power of any mill is proportional to the speed during milling. At this stage residence time of particles cling on the blades is minimum, hence least abrasive. Most work on the understanding of how particles abrade blades as well as power models has been centred on the steady state stage conditions.

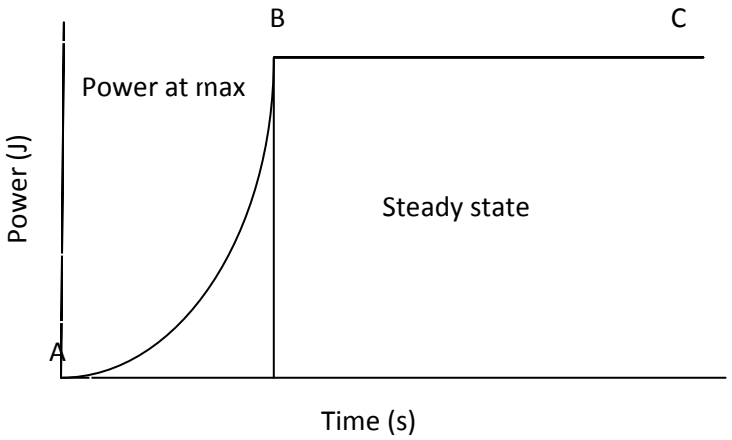


Figure 23: Diagram showing how power is consumed with time during milling

A study by Misra and Finnie (1981) explained that, at steady state there is no time for the heat (energy) to be transferred into the material being abraded, and because of this, the stress of the surface of the blades induced through grinding will drop, thereby reducing the abrasion effect (residence time dependent). In short abrasion is high at phase A-B and drops (or remains constant) significant at steady state, and will cause a deceleration when a mill comes to the stop after trajectory BC.

Equation (10) is used to calculate the average torque of the mill which is used into calculating the energy used by a mill during comminution. The values are tabulated in Table14 below. Also included is the difference in energies between Phase A-B and Phase B-C as shown by Figure 23. This energy difference tells one the energy used by a mill to produce heat (friction between material and coal particles) which in turn leads to the blades being abraded, or simply the energy is used in creating the new surface area of a solid particle.

Energy values reported in Table14 are the energies the mill consumed to create a new particle during comminution. This energy is for the whole motion until the rotor came to rest. That is, the energy from initial velocities until steady state. Energy of about 74.35 kJ was obtained using the steady state formula given in Nikolov (2002). From this energy value and the tabulated energies, the difference in energy representing the energy used into create a new surface can be known. This is the energy a mill will consume before reaching steady state. This energy is important in a

sense that it can be used to calculate the powers required during early stages of grinding from which it is believed to be proportional to velocity. At this stage heat is known to result which is transferred into the material surface thereby leading to material wear off. By calculating these powers, it can be ascertained at what stage was abrasion highest on the grinding elements.

Table 14: Torque, Energy and Power values

Coal Name	Torque (Nm)	Energy (kJ)	Energy difference (kJ)	Power (kJ/s)
Coal A	0.121	760	685.65	1.63
Coal B	0.118	741	666.65	1.55
Coal C	0.117	735	660.65	1.52
Coal D	0.118	741	666.65	1.55
Coal E	0.116	729	654.65	1.50

Energy and power values tabulated in Table14 suggest that Coals B and D can be of same strength even though their AI values are of great difference (namely 115.6 mg/kg and 85.7 mg/kg respectively). A similar observation is given by Coals C and E which have AI values of 28.63 mg/kg and 51.15 mg/kg respectively. The energy difference illustrates plainly that apart from Coals B and D, and Coals C and E showing same breakage, Coal A utilised most power, which could mean it was most resistive to breaking, and hence is abrasive.

One can ask why one would go to such extremes to understand how torque is influenced by time? The real sense is that, apart from energy, but through calculations that involve energy, the abrasion properties of coals can be evaluated. Properties of coals such as abrasion factor, intensity of abrasion, wear resistance and comminution index can be determined empirically. The

latter is directly related not only to the coal properties but also to the properties of the grinding system. This coal property is the quantity that can be used to evaluate the ease at which coal was ground or can be crushed (grindability), which in return can be directly related to abrasion. The intensity of abrasion is an important inherent property of coal since it is used to evaluate the coal bed moisture (Spero, 1990).

The most important property of coal that is realised, based on the energy with which the machine pulverise coal, is the work index (W_i). This quantity, introduced by Bond (1952) cited in (Warren Spring Laboratory, 1962),and (Scieszka, 1985), is used to evaluate the relative residence of coal consisting of different small coal masses (dm), the efficiency of machine and other different process during tests (Spero, 1990). This index is used to calculate the definite energy applied in reducing coal of infinite particle size to at least 80% that will pass the 75 μm mesh (Scieszka, 1985). The values are given in Table 15.

Table15 shows the statistical values of abrasion intensity, abrasion factor, wear resistance and work index respectively. AI_i and AF_i together represent the abrasion property of coals, and are also used to establish through predictions the longevity of the blades, with WR_i being indicative of the materials resistance to wear. IC is indicative of the ease with which coals can be ground. Wi only indicates the energy inputs that a mill will need to achieve a pulverised coal.

Table15 indicates that Coal B has high values of AF and AI_i followed by Coal A, D, E then C respectively. IC indicates that Coal B and A ground with difficulty. Wear resistance (WR_i) is low for Coals B, A and D respectively, least for Coal C and medium for Coal E. High energy input was used by the abrasion tester pot to grind Coals B and A, which was then equivalent for the other coals.

Table 15: Abrasion intensity (AI_i), abrasion factor (AF_i), wear resistance (WR_i) and work index (WI_i) values

Coal Name	AI_i (mg $m^{-2}s^{-1}$)	AF_i(mg kg^{-1})	WR_i (kJ/mg)	WI_i (kJ/g)	IC(mg/kg)*1E06
Coal A	873.50	288.76	4.35	4.29	796.05
Coal B	1216.58	608.29	3.21	4.88	512.82
Coal C	286.25	82.97	12.84	4.02	931.17
Coal D	857.00	246.62	4.32	4.04	937.92
Coal E	511.50	157.38	7.13	4.02	891.63

Table 15 and Table 3 together tabulate the mechanical properties of coal samples used here. From both tables it is evident that when AI_i and AF are high AI is high, and when AI_i and AF are low AI is low. This is shown by Coal B and Coal C respectively. Coal E has the smallest AF and AI_i values, this holds since this coal is least abrasive (Coal C is not abrasive, indicated by the AI values). Tables 3 and 15 also indicate that when AI values are high, wear resistance is low, indicated by Coal B, A and D respectively. The reverse holds, indicated by Coal C and E respectively.

From Table 15 it is clear that abrasion intensity was increasing from Coals C, E, D, A to Coal B respectively. This was anticipated since AI is a function of coal bed moisture (Spero, 1990), which varies logarithmically with temperature (Spero, 1990; Coldham, 1989). The moisture content of this coals is reported in Table 2, which is high for Coal B and A respectively. Sengupta (2002) using Indian coals, has shown that, when wear resistance decrease the grindability values will increase. Looking at the values of WRi and IC reported in Table15, this becomes apparent.

In summary, it can be said with certainty that AI_i and AF are coal mechanical properties that are closely related to abrasion index. When wear resistance is low, it would mean coals are abrasive and vice versa, similarly for index of communition. The study corroborates the fact that abrasive coals are power intensive. This is ascertained by the work index values reported, which are high for abrasive coals and low for less or non abrasive coals.

4.11. Addition section on Multilinear analysis (required by the examiner)

Multilinear regression analysis is applied to experimental data when researchers want to investigate the relationship between independent variables and dependent variables. Multilinear regression analysis can be performed using computer mathematical software's. Typical excel add-in functions are there as tools used to solve multilinear regression equations; equally so are Matlab computer mathematical software's. These two software's, Matlab and excel-Linest, were used (for comparison reason) to give coefficients of Equation 11 such that a general linear equation describing AI as a function of coal constituents is known. The equation was used to indicate, conclusively which of the coal constitutes studied and discussed above are the key factors which influenced abrasion index of the coal samples.

$$Yi = M_1X_1 + M_2X_2 + M_3X_3 + \cdots + M_nX_n \quad (11)$$

Equation 11 is a general linear equation of finite set of data used to fit experimental data such that meaning is given to the data. For this study, a 5 X 13 matrix (see Table C1, Appendix C) need to be solve such that only those coal constituents that strongly correlates with AI be concluded. From the spread sheet obtained (ANOVO-Lines as attached in Appendix C, Table C3) which showed the estimated coefficients of the independent variables the following equation was generated:

$$Y_{comp} = 2.45\,X_2 + 1.33X_3 - 1.53X_4 + 1.68X_6 - 0.24X_{11} \quad (12)$$

Where in equation (12): Ycomp refers to the Y values of the computer fitted function;

X_2, X_3 X_4, X_6, and X_{11} refer to HGI, vitrinite, inertinite, carbominerite (included minerals), and quartz respectively. By substituting all the X values from the experimental data into equation (12) we are able to determine Ycomp values, which are reported in Table 16. Note that a coefficient of total moisture ((X1) and total mineral matter (X7) are zero, this is true since basic excel gave an exponential behaviour and here a linear line was fit through data points.

To understand or give meaning to this equation, estimated experimental variance (S^2), sum of the square residual (SSR: Difference between experimental value of the response and a computer value), R^2, and adjusted R^2 were calculated using the following equations respectively; data which is reported in Table 16:

$$SSR = \sum(Y_i - Y_{comp})^2 \quad (13)$$

$$S^2 = \frac{\sum(Y_i - Y_{comp})^2}{N-P} \quad (14)$$

$$\bar{Y}(Exp\ mean) = Yi/5 \quad (15)$$

$$R^2 = 1 - \left(\frac{SSR}{Yi-\bar{y}}\right)^2 \quad (16)$$

$$Adjusted\ R^2 = \left(\frac{SSR}{1-R^2}\right) \quad (17)$$

Where N=number of experiments, and P=number of coefficients of the computer produced model.

Typically, regression analysis is said to give good results when a R^2 is close to 1, and SSR is small. Table 16 indicate that the input Y (or experimental Y values) is not that far when comparing to computed Y values. Given the understanding that when SSR and R^2 are small results are good, then it may be concluded that the results as shown in the Table 16 are good, indicating that the experimental data was not that far out from the computed results.

Table 16: Multilinear regression data

Yi (Exp)	Y comp	SSR	S^2	Y (Exp Mean)	Adjusted R^2	R^2
87.4	87.90	0.25	0.05	73.7	187.69	0.998678651
115.6	116.00	0.17	0.03	73.7	1755.61	0.999903313
28.6	29.10	0.27	0.05	73.7	2034.01	0.999869098
85.7	86.10	0.16	0.03	73.7	144.00	0.998888889
51.2	51.60	0.12	0.03	73.7	506.25	0.999744

In comparison, results obtained using basic excel curve fitting concluded that total moisture, excluded and included mineral or carbominerite, inertinite and vitrinite will influence abrasion of coals. On the contrary basic excel did not find any significant relationship between AI and HGI, but Linest and Matlab concluded, in addition to what basic excel revealed to being the constituent of coals that influences AI (excluding total moisture and excluded minerals), HGI to have a linear influence on AI of coal samples. Linest or Matlab would not find a linear trend between AI and total moisture and AI and excluded minerals respectively since they were exponentially impact on AI. In conclusion, it would be said here that even though basic excel work for data point fitting it has limitations; as indicated by relationship between AI and HGI, which therefore means multilinear regression analysis must be used for as a primary tool in statistical analysis for experimental data analysis such that valuable information is extracted from the obtained experimental data.

CHAPTER 5: CONCLUSIONS

At the begin of this work it was stated that this study serves as part of a larger project that will aim at devising a standard method acceptable for testing coals for abrasion in South Africa. Currently in South Africa there is no acceptable standard method for testing coals for the abrasion index. The technique referred to as YGP (Yancey, Geer and Price) proposed and accepted in 1951 is most commonly used for test coals for the abrasion index. Over the years there have been some modifications to this method both by mining houses and coal users (such as Eskom) which have resulted in inconsistent and conflicting results. This study primarily sought to establish the key characteristics of coals that influence abrasion during grinding.

In this study five South African ROM coals were characterised both chemically and physically using techniques and methodologies that are discussed in Chapter 3. For chemical analysis X-ray Fluorescence and FEI Quanta 200 scanning electron microscope fitted with Oxford INCA 400 energy dispersive X-ray were used. For the organic and inorganic matter analysis, a Leica DM4500P petrography microscope, X-ray diffraction (PANalytical X'Pert Pro powder diffractometer with X'Celerator detector and variable divergence- and fixed receiving slits with Fe filtered Co-Kα radiation) were used.

Hardgrove machine, Abrasion index tester pot and the sieve method were used to determine the grinding properties of the coal samples. These grinding properties are referred to as HGI, AI, and PSD respectively. Perkin-Elmer simultaneous thermogravimetric analyser (STA 6000) equipped with Pyris Manager Software was used for proximate analysis. A Labcon moisture oven was used to analyse for the inherent moisture of the coal samples. FEI Quanta 200 SEM fitted with an Oxford INCA 400 EDS was used primarily for the characterisation of the blades surface topography, particle shape and particle morphology. The energy utilised by the grinding machine was calculated using energy models, this help to further establish the grinding properties of coal. Abrasion factor, abrasion intensity, wear resistance, and work index were calculated using energy and PSD results.

The results obtained from all the listed analytical techniques indicate that moisture was the only chemical constituent that affected abrasion of the coal samples. Ash content did not appear to influence AI of coal samples. Coal physical properties that have influenced abrasion were included minerals (carbominerite), vitrinite and vitrinite rich microlithotypes, and excluded minerals including clay and quartz. The results on rank and abnormal conditions indicate that all coal samples were Medium rank C type coals (Iso-rank) and only Coal C might have been weathered. Weathered coals were identified to be soft and not abrasive when compared to unweathered coals. AI_i and AF appear to influence abrasion of the coal samples. It was shown by this study that abrasion index increased with increasing AF and AI_i; together. Also demonstrated is the fact that work index values are proportional to AI values. The higher is the working index of coals, the higher is the resulting AI. PSD analysis concluded that coarse particles are very abrasive, and SEM morphology analysis indicated that non round and sharp coal particles are abrasive.

In addition to the stated primary goal, this study specifically sought to address the points given below together with their findings.

(1) Determine if the Abrasion Index (AI) and Hardgrove Grindability Index (HGI), empirical correlations as developed by Scieszka (1985), can be verified using experimental results. It transpired from this study that AI and HGI are independent of one another. This therefore might suggest that grindability alone cannot be used to establish abrasion property of the coal samples.

(2) Determine if excluded minerals and included minerals are equally abrasive. It was shown that excluded minerals are as highly abrasive as minerals contained in coal's organic matter (carbominerite). This was ascertained by correlating the petrographically identified mineral constituents to the AI values obtained for all the coal samples. See Figure 15 and Figure 17 respectively. This therefore means it is equally important that included mineral be considered when wear is studied as oppose to only reporting wear as a function of excluded minerals such as pyrite and quartz.

(3) Establish the type of abrasive wear that occurred during coal grinding. Three body abrasive wear was established to be the main wear during grinding in an abrasion index tester pot. This was established from the surface topography of the blades obtained using SEM (see Figure 9).

This might infer that predominantly three-body abrasive wear will result when coals are ground, even in mills used at the industry to reduce coals.

Literature stated that moisture and ash content, inertinite rich coals, and minerals constituents such as pyrite and quartz, and bimaceral and trimaceral microlithotypes amongst other coal constituents have an influence on abrasion index of coals. In contrast, this study demonstrated that ash content appears to have no influence on coal's abrasiveness, and vitrinite rich coals have an impact on the coals' abrasiveness. In addition vitrite, a monomaceral comprising of 95% of vitrinite macerals, was noted as one of the constituents that has an influence on AI of coals. This study further showed that clays and quartz, and not pyrite, did influence the reported AI values of the coal samples. This study supports the observation that moisture, and quartz influence abrasive quality of coals. Also corroborated is the observation that excluded minerals, and carbominerite contribute greatly to the abrasive quality of coals. Minerals reported for this study were determined using petrography (point count method) and XRD with Siroquant software capable of doing Rietveld analyses (qualitative method).

Thus the overall factors affecting the abrasive quality of coals are divided below into sub-classes: the chemical and physical properties.

5.1. Chemical constituents influencing abrasive quality of coal is:

a. Total moisture

5.2. Physical constituents of coals influencing abrasive quality were:

a. Minerals such as clays and quartz (silicates)
b. excluded minerals, included minerals, inertinite and vitrinite

5.3. Grinding (or abrasion) properties affecting abrasive quality of coals were:

a. Particle size (coarse) and morphology (non-round)
b. Abrasion intensity and abrasion factor (together)
c. HGI (confirmed by multilinear regression analysis)

CHAPTER 6: BENEFITS, RECOMMENDATIONS AND FUTURE WORK

The results reported for this research can be used as a guideline for the selection of materials that can be used into making the blades such that wear on mills is reduced. Not only the results of this research can be used for material selection, but they can also be used to understand how long the new developed cutting blades can last when used in a large scale pulverising machine. This therefore will help improve maintenance, and reduce cost related to wear. That is, the results herein may act as a control to maintenance, and help in choosing of materials that will potentially be resistive to wearing from which mill cutting blades and components can be made or constructed.

Recommendations that arise during this work are:

1. Results found here have to be compared to the full scale comminution results using a mill fitted to the actual boiler. This helps by understanding if abrasion index study on a laboratory scale can be used to predict what will happen at full scale.
2. Abrasion index tester pot needs to be designed such that an energy measuring device can be fitted to it; this eliminates errors and the approximations in calculation done here-in using empirical formula. This is said owing to the fact that power utilised in every engineering process is of importance therefore it has to be thoroughly studied.
3. Corrosion-abrasion phenomena should be studied during comminution. This is because water or residue that formed on the coal container and lid during comminution using an abrasion index tester pot could have been contained and analysed for the pH, which can be used in determining corrosion mechanism.
4. Many coal samples need to be tested to see if the results are reproducible thereby adopting the abrasion index method used here towards formulating a South African abrasion index standard method. That is, formulating SABS for testing AI of coals.

Future work can embrace the making of the blades following these results, thereby using them to study abrasion index, when the study seeking to establish the South African abrasion index standard method is undertaken.

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Appendix A: Raw Data and Spectrum

A.1: Moisture

Table A1: Free moisture values (Air dry basis)

Coal name	Buckets masses	Initial mass	Final mass	Free Moisture	Free Moisture (%)
Coal A	820	15630	15285	0.0	2.2
Coal B	820	16410	15485	0.1	5.9
Coal C	820	18325	18000	0.0	1.9
Coal D	815	20600	20295	0.0	1.5
Coal E	810	20100	19745	0.0	1.8

Table A2: Inherent moisture values (Air dry basis)

Coal name	Trial 1 (%)	Trial 2 (%)	Trial 3 (%)	Inherent moisture (%)
Coal A	4.0	4.4	4.5	4.3
Coal B	5.4	4.7	4.5	4.9
Coal C	2.4	2.5	2.7	2.5
Coal D	2.3	2.5	2.7	2.5
Coal E	2.9	2.6	3.4	3.0

Results in Table A2 were determined using a moisture oven following method described in Lenahan and Murray-Smith (1986). This method calculates moisture of coals as function of change in weight. The initial weight (weight before heating at a range of 105°C- 110°C) is subtracted from the resulting weight after 1hr 30 minutes of heating. As indicated in Table A2, three trials were taken. The reported results were used with confidence after being confirmed by an accredited laboratory called Witlab, which returned the same results. Using Formula B2 it was possible to calculate the reported total moisture of the coal samples.

Table A3: Inherent moisture (Witlab results)

Sample Identity	**H_2O (%)**
COAL A	4.3
COAL B	3.9
COAL C	2.9
COAL D	2.3
COAL E	2.5

Table A2 and Table A3 report results obtained using two different techniques. It is evident from the tables that results are comparable with significant difference shown by Coal B only.

A.2: raw data obtained using analytical techniques

A.2.1. Proximate analysis profiles

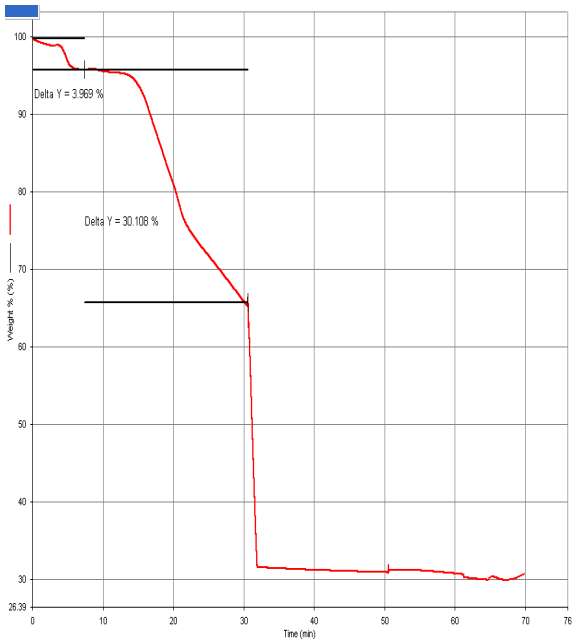


Figure A1: TGA profile for Coal A

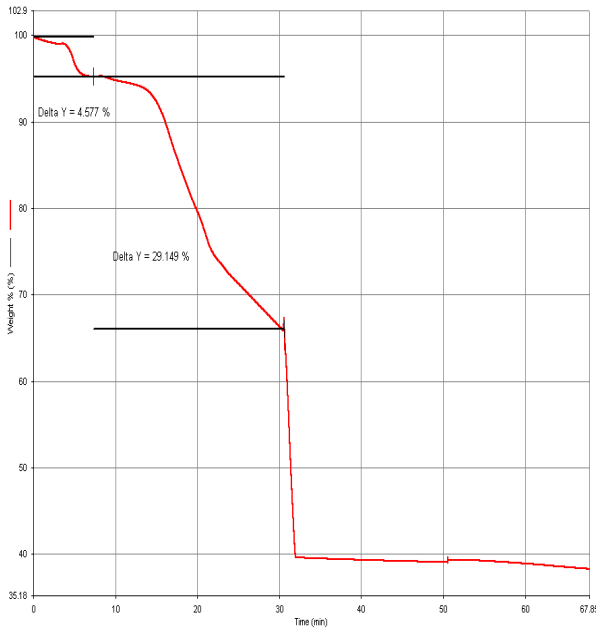


Figure A2: TGA profile for coal B

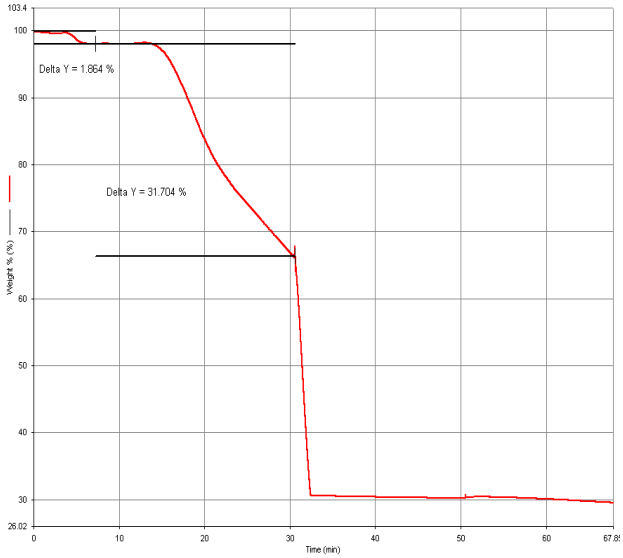


Figure A3: TGA profile for coal C

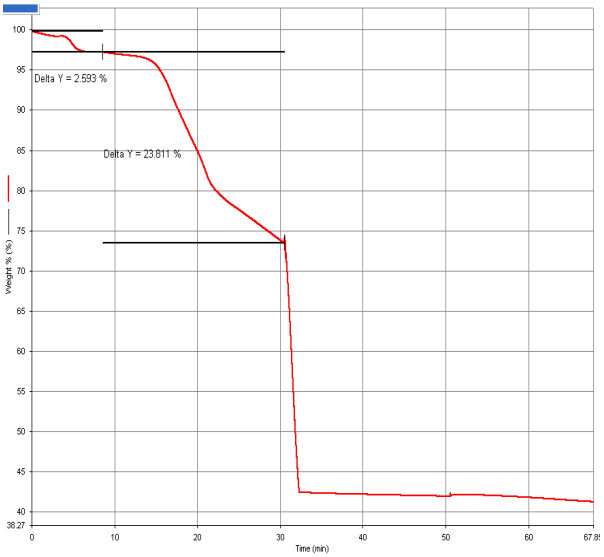


Figure A4: TGA profile for coal D

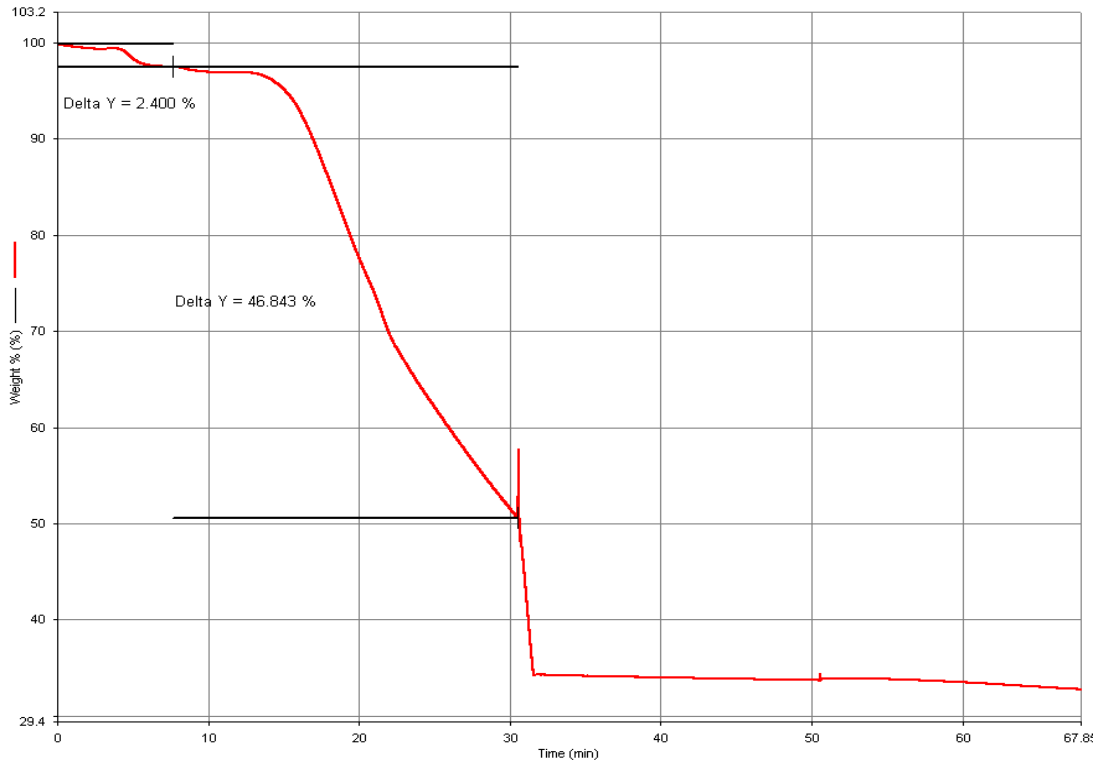


Figure A5: TGA profile for coal E

A.2.2: Petrography

Table A4: Macerals analyses

TABLE 1: MACERAL GROUP ANALYSIS % (ISO 7404 - 3, 1994)						
Maceral Group	**Maceral Sub Group**	**Coal name**				
		Coal A	**Coal B**	**Coal C**	**Coal D**	**Coal E**
VITRINITE	**Collinite**	15.2	30.2	7.0	9.4	14
	Pseudovitrinite	0.0	0.8	0.0	0.0	0.2
	% Total Vitrinite	**15.2**	**31.0**	**7.0**	**9.4**	**14.2**
LIPTINITE	**S/R/C**	4.8	4.4	5.0	2.8	1.6
	Alginite					
	% Total Liptinite	**4.8**	**4.4**	**5.0**	**2.8**	**1.6**
INERTINITE	**RSF**	4.6	1.4	2.6	0.4	6.2
	ISF	29.6	16.6	30.2	24.0	17.2
	F / SEC	3.0	4.0	3.0	2.0	6.0
	MIC	0.8	0.0	0.8	0.2	1.4
	RINT	1.4	0.6	2.4	0.2	1.4
	IINT	23.8	21.2	35.4	30.2	32.0
	% Total Inertinite	**63.2**	**43.8**	**74.4**	**57.0**	**64.2**
% TOTAL REACTIVE MACERALS		**48.4**	**37.4**	**17.0**	**12.8**	**23.4**
Mineral Matter	**clays & quartz**					
	pyrite					
	carbonates					
% TOTAL MINERAL MATTER		**16.8**	**20.8**	**13.6**	**30.8**	**20.0**

Table A5: Microlithotype Group Analysis (ISO 7404-4, 1994)

Group	f.o.v.	Microlithotype		Coal name				
				Coal E	Coal B	Coal D	Coal C	Coal A
Monomaceral	>95%	Vitrite		9.6	23.8	8	4	11.6
		Inertite	Semi-Fusite(SF)	26	15.4	11	33.2	28.8
			Fusite (F)	9.2	2.6	3	0.2	2.4
			Inertodetrite	26.4	26	40	46.8	28
		Liptite		0	0	0	0	0
Bimaceral	<95%	Vitrite+SF/ F		2.8	1.6	1.2	2.4	0.8
		Vitrite + Inertodetrite		2.4	2.4	1.4	2.6	2.2
		SF+ Inertodetrite		2.2	0.2	0.6	0.8	1.2
	Clarite	Vitrite + Liptite		0.4	0.8	0.2	0.4	0.6
	Durite	Inertite + Liptite		2	2.4	3.4	2.4	2
Trimaceral	Each >5%	Vitrite + Inertite + Liptite		2	2.2	1.8	0.8	2.4
Carbominerite	20-60%	Carboargilite		2.2	4.4	9.2	4.4	4.6
	5-20%	Carbopyrite		1.8	1.6	0.2	0.6	2.6
		Carboankerite		1.4	1.6	1.4	0.2	2.6
		Carbosilicate		4.6	4.4	9.2	0.6	2.2
		Carbopolymineral		0	0	0.2	0	0
Rock	>60%MM	Rock		7	10.6	9.2	0.6	8
Key Values	f.o.v.			Coal E	Coal B	Coal D	Coal C	Coal A
	>95%	Vitrite		9.6	23.8	8.0	4.0	11.6
	BI & TRI	Intermediate		11.8	9.6	8.6	9.4	9.2
	>95%	Semi-Fusite/ Fusite		35.2	18.0	14.0	33.4	31.2
	>95%	Inertodetrite		26.4	26.0	40.0	46.8	28.0
		Sapropelic		0.0	0.0	0.0	0.0	0.0
	5-60%	Carbominerite		10.0	12.0	20.2	5.8	12.0
	>60%	Rock		7.0	10.6	9.2	0.6	8.0

Table A6: Rank analyses (ISO7404 - 5, 1994)

		Coal E	Coal B	Coal D	Coal C	Coal A
RoVmr%		0.72	0.62	0.70	0.73	0.63
Standard deviation		0.092	0.072	0.08	0.13	0.08
Range	low	0.54	0.47	0.51	0.54	0.51
	high	0.91	0.85	0.96	1.04	0.96
RANK CATEGORY		med Rank C	med rank C	Med Rank C	med Rank C	med rank C

Table A6 presents coal rank analyses. The coals were Iso-rank. Coal C was possibly weathered.

Table A7: Key variables

f.o.v	**field of view**	**carboargilite =**	**Clays**
Sf	Semifusite	carbopyrite =	Pyrite
F	Fusite	carboankerite =	Carbonates
Mm	mineral matter	carbosilicate =	Quartz
		carbopolyminerals =	mixed

Table A8: Coal Abnormal Condition (CAC) analysis

GROUP	**CONDITION**	Coal A	Coal B	Coal C	Coal D	Coal E
Fresh	total fresh	68	69	68	80	80.5
Fissures	Few	10.3	14.3	10.5	5.8	5.3
	Intense	2.3	2.0	1.5	0.5	0.8
Cracks	Few	6.3	5.8	2.5	3.3	4.3
	Intense	0.0	0.0	1.5	0.0	0.0
	Desiccated	0.0	0.0	0.0	0.0	0.5
Holes	Leached	2.8	0.8	3.8	0.5	0.5
	Inherent	5.1	2.5	2.8	3.8	5.5
	porous fusinite	4.3	2.8	3.8	2.8	2.0
Heat affected	Organic	0.0	0.0	0.0	0.0	0.0
	inorganic / minerals	0.0	0.0	0.0	0.0	0.0
Discolouration	whole particle	1.3	3.0	5.3	3.5	0.8
	dark zones	0.0	0.0	0.5	0.0	0.0
	light zones	0.0	0.0	0.0	0.0	0.0
Total abnormal condition		32.4	31.2	32.2	20.2	19.7

Table A9: Mineral Distribution Analysis

GROUP	f.o.v. %	Coal name				
		Coal E	**Coal B**	**Coal D**	**Coal C**	**Coal A**
CLAYS	5 – 20	38	68.2	57.2	71.8	75.4
	20 – 60	4	9.2	24.8	2.6	2.4
	>60	2.2	7.2	4.8	0.4	1.8
	TOTAL	**44.2**	**84.6**	**86.8**	**74.8**	**79.6**
QUARTZ	5 – 20	22	1.8	2.2	5.2	5.4
	20 – 60	7.6	1.6	1.2	0.8	1.2
	>60	5.4	0.2	1	0.4	1.2
	TOTAL	**35**	**3.6**	**4.4**	**6.4**	**7.8**
PYRITE	5 - 20	1.8	2	0.8	1	4
	20 - 60	1	0.6	0.6	0.2	0.6
	>60	1	0.6	0	0	0.6
	TOTAL	**3.8**	**3.2**	**1.4**	**1.2**	**5.2**
CARBONATES	5 - 20	1	1.2	1.6	0.6	1.8
	20 - 60	1.2	1.8	1.8	0	1.6
	>60	3	1.4	2.2	0	2.2
	TOTAL	**5.2**	**4.4**	**5.6**	**0.6**	**5.6**
OTHER MINERALS	5 - 20	0.2	0	0.6	0.6	0
	20 - 60	0.2	0.2	0	0	0
	>60	0	0.2	0.4	0.2	0.8
	TOTAL	**0.4**	**0.4**	**1**	**0.8**	**0.8**
NO VISIBLE MINERALS	<5	11.4	3.8	0.8	16.2	1

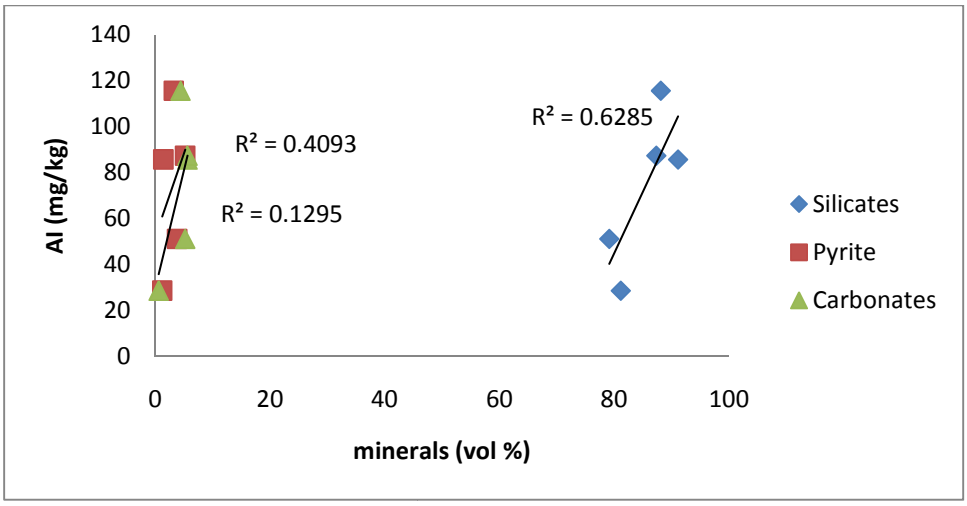


Figure A6: Effects of minerals on AI

A.2.3.: XRD spectra

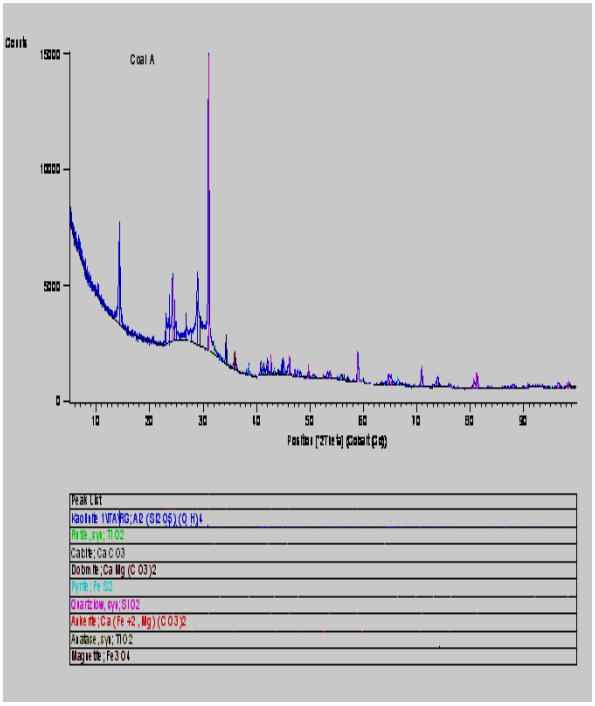


Figure A7: XRD spectrum for Coal A

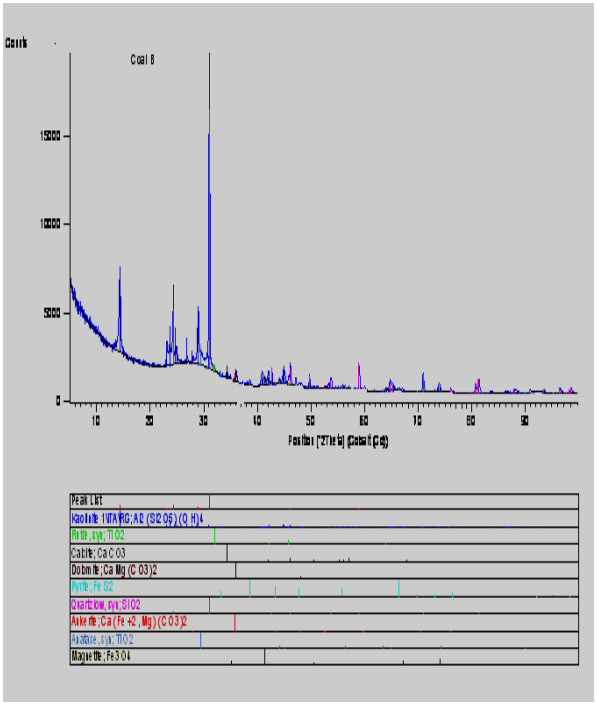


Figure A8: XRD spectrum for Coal B

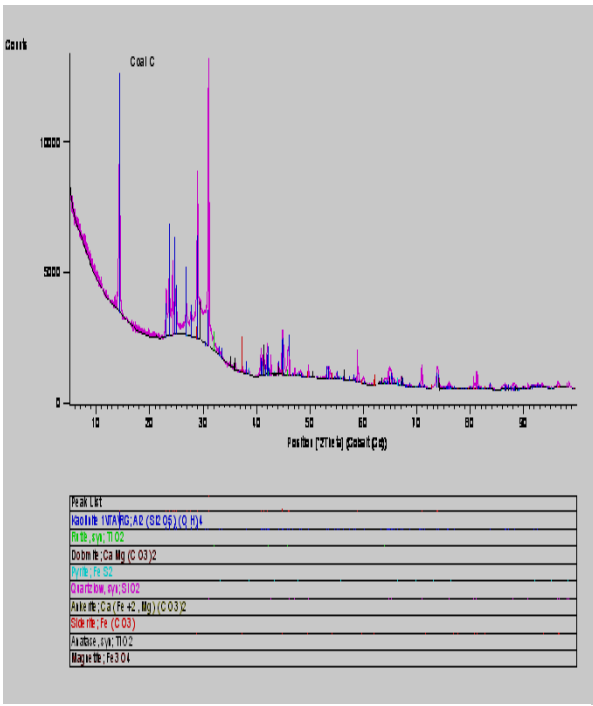


Figure A9: XRD spectrum for Coal C

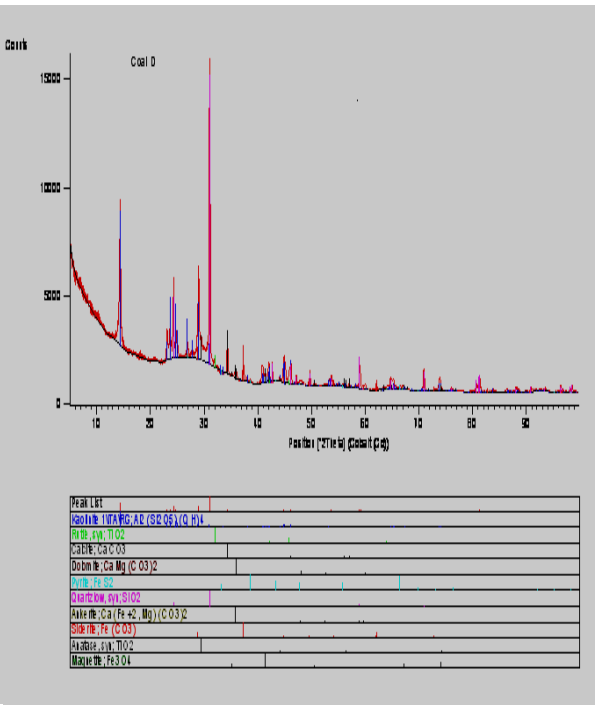


Figure A10: XRD spectrum for Coal D

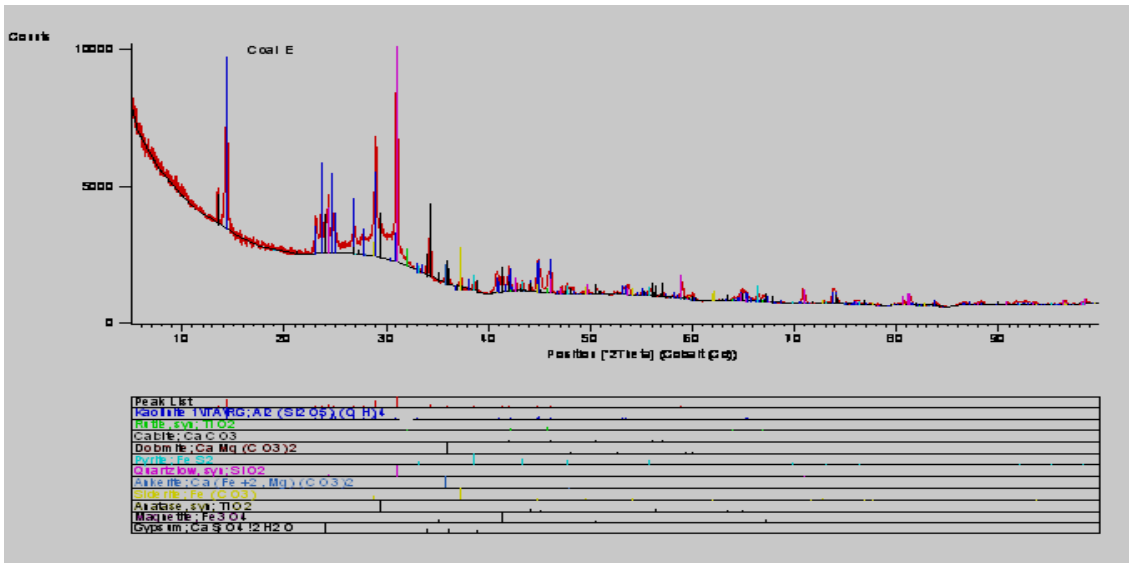


Figure A11: XRD spectrum

A.2.4: SEM-EDS raw data

Table A10: Coal A SEM- EDS results

Element	Weight (%)	Atomic (%)	Compound (%)	Formula
C	25.07	31.38	91.87	CO2
Mg	0.08	0.05	0.13	MgO
Al	1.32	0.73	2.49	Al2O3
Si	2.08	1.11	4.44	SiO2
S	0.10	0.05	0.26	SO3
K	0.08	0.03	0.10	K2O
Ca	0.30	0.11	0.43	CaO
Ti	0.06	0.02	0.11	TiO2
Fe	0.14	0.04	0.18	FeO
O	70.76	66.48		

Table A11: Coal B SEM- EDS results

Element	Weight (%)	Atomic (%)	Compound (%)	Formula
C	24.17	30.54	88.55	CO2
Mg	0.11	0.07	0.19	MgO
Al	1.81	1.02	3.42	Al2O3
Si	2.98	1.61	6.37	SiO2
S	0.18	0.09	0.45	SO3
K	0.10	0.04	0.12	K2O
Ca	0.37	0.14	0.52	CaO
Ti	0.09	0.03	0.15	TiO2
Fe	0.18	0.05	0.23	FeO
O	70.01	66.42		

Table A12: Coal C SEM- EDS results

Element	Weight (%)	Atomic (%)	Compound (%)	Formula
C	25.66	31.94	94.04	CO2
Al	0.98	0.54	1.85	Al2O3
Si	1.36	0.72	2.91	SiO2
S	0.13	0.06	0.33	SO3
Ca	0.07	0.02	0.09	CaO
Ti	0.09	0.03	0.15	TiO2
Fe	0.49	0.13	0.63	FeO
O	71.22	66.55		

Table A13: Coal D SEM- EDS results

Element	Weight (%)	Atomic (%)	Compound (%)	Formula
C	23.89	30.31	87.53	CO2
Mg	0.11	0.07	0.18	MgO
Al	2.12	1.20	4.01	Al2O3
Si	3.06	1.66	6.54	SiO2
P	0.07	0.04	0.16	P2O5
S	0.07	0.03	0.18	SO3
K	0.13	0.05	0.15	K2O
Ca	0.48	0.18	0.67	CaO
Ti	0.14	0.04	0.23	TiO2
Fe	0.27	0.07	0.35	FeO
O	69.67	66.35		

Table A14: Coal E SEM- EDS results

Element	Weight (%)	Atomic (%)	Compound (%)	Formula
C	25.80	32.04	94.53	CO2
Mg	0.05	0.03	0.08	MgO
Al	0.93	0.52	1.77	Al2O3
Si	1.24	0.66	2.66	SiO2
S	0.13	0.06	0.31	SO3
Ca	0.24	0.09	0.33	CaO
Ti	0.06	0.02	0.09	TiO2
Fe	0.17	0.05	0.22	FeO
O	71.38	66.55		

Appendix B: Equations used in this study

B.1: Formulas used to calculating results:

Moisture:

$$\%Free\ moisture\ = \frac{W_2 - W_1}{W_3 - W_1} \times 100\% \quad \text{(B1)}$$

$$\%\ Total\ Moisture = X + M_0\left(1 - \frac{X}{100}\right) * 100 \quad \text{(B2)}$$

Abrasive index: *Wear of blade*

$$W = M_1 - M_2 \quad \text{(B3)}$$

$$AI = \frac{\Delta W}{Feed\ mass} \quad \text{(B4)}$$

$$AI = f(HGI, B) \quad \text{(B5)}$$

Where B is the tribological properties of grinding machine

Energy consumption:

$$\tau = \frac{1}{td}\int_0^{td} \tau(t)\, dt \quad \text{(B6)}$$

Where: τ (t) is torque that is time dependent, τ is average integral value of torque (Nm), and t_d is the time it takes a grinder to complete 12000 revolutions

$$EI = 2\Pi\tau \quad \text{(B7)}$$

EI energy input (J) by a mill when 2kg of coal sample is rotated at one complete revolution

Mechanical properties of coals:

Abrasion factor of coal:

$$AF = \frac{\Delta W}{PC} \quad \text{(B8)}$$

Intensity of abrasion:

$$IA_i = \frac{\Delta W}{Std} \quad \text{(B9)}$$

Where: S=area of blade surface exposed to wear (m)

Work index:

$$W_i = W\left(\frac{F}{F-P}\right)^{0.5}\left(\frac{P}{75}\right) \quad \text{(B10)}$$

Index of comminution of coal:

$$IC = \frac{PC}{EI} \quad \text{(B11)}$$

Wear resistance of material:

$$WR = \frac{EI}{\Delta W} \quad \text{(B12)}$$

B.2. Prove of integral-torque formula:

$$E = \frac{1}{t}\int_0^t \tau(t)\, dt \quad \text{(B13)}$$

$where\ t, \tau\ and\ dt\ are\ time, torque\ and\ change\ in\ time\ respectively$

From laws of motion, we know by definition that:

$$\tau = I\alpha \quad \text{(B14)}$$

$where\ \tau, I\ and\ \alpha\ are\ torque, mass\ moment\ inertia\ and\ angular\ accelation\ respectively.$

Also, $\alpha = \frac{d\omega}{dt}$ (B15)

$where\ \frac{d\omega}{dt}\ is\ change\ in\ angular\ velocity$

Substituting (B15) into (B14), equation (B14) is reduced to:

$$\tau = I\,\frac{d\omega}{dt} \quad \text{(B16)}$$

When equation (B16) is re-arranged and the integral taken, it reduces to:

$$\int_0^t \tau \, dt = I \int_0^\omega d\omega \qquad \text{(B17)}$$

Comparing equation (B13) and (B17), when equation (B13) is re-arranging, the right-hand side of equation (B13) is the same as the left-hand side of equation (B17) and can be equated. After the two equations are equated the results are:

$\tau \, t = I \int_0^\omega d\omega$, which will reduce to

$$\tau \, t = I \, \omega \qquad \text{(B18)}$$

The boundary conditions used are:

$$\tau(t) = \begin{cases} -t, & x < 0 \\ t, & x \geq t \end{cases} \quad \text{and } d(\omega) = \begin{cases} \omega_0, & x < 0 \\ \omega, & x \geq \omega \end{cases}$$

Therefore $\tau \, (t) = \frac{I\omega}{t}$ This completes the proof.

B.3: Abrasion index data

Table B1: Raw data used to calculate AI and temperature readings

Coal A						
Mass of Blades loss	Sample 1	Sample 2	Extra turns	Temperature Analysis		
M1(g)	91.8992	91.7206	11	T1	21	21
M2(g)	91.7206	91.5498	11	T2	51	52
ΔM	0.1786	0.1708		ΔT(°C)	30	31
ΔM(mg)	178.6	170.8				
AI(mg/Kg)	89.3	85.4				
$\bar{A}\bar{I}$(mg/Kg)	87.35					
Coal B						
Mass of Blades loss	Sample 1	Sample 2	Extra turns	Temperature Analysis		
M1(g)	91.5517	91.3231	11	T1(°C)	23	23
M2(g)	91.3231	91.0894	11	T2(°C)	59	58
ΔM	0.2286	0.2337		ΔT(°C)	36	35
ΔM(mg)	228.6	233.7				
AI(mg/Kg)	114.3	116.85				
$\bar{A}\bar{I}$(mg/Kg)	115.575					
Coal C						
Mass of Blades loss	Sample 1	Sample 2	Extra turns	Temperature Analysis		
M1(g)	90.7251	90.6658	12	T1	20	22
M2(g)	90.665	90.6114	12	T2	60	63
ΔM	0.0601	0.0544		ΔT	40	41
ΔM(mg)	60.1	54.4				
AI(mg/Kg)	30.05	27.2				
$\bar{A}\bar{I}$(mg/Kg)	28.625					
Coal D						
Mass of Blades loss	Sample 1	Sample 2	Extra turns	Temperature Analysis		
M1(g)	90.8946	91.1144	10	T1	21	20
M2(g)	90.7251	90.9411	10	T2	65	58
ΔM	0.1695	0.1733		ΔT	44	38
ΔM(mg)	169.5	173.3				
AI(mg/Kg)	84.75	86.65				
$\bar{A}\bar{I}$(mg/Kg)	85.7					
Coal E						
Mass of Blades loss	Sample 1	sample 2	Extra turns	Temperature analysis		
M1(g)	91.3149	91.2168	11	T1	21	21
M2(g)	91.2168	91.1103	11	T2	59	61
ΔM	0.0981	0.1065		ΔT	38	40
ΔM(mg)	98.1	106.5				
AI(mg/Kg)	49.05	53.25				
$\bar{A}\bar{I}$(mg/Kg)	51.15					

B.4: *Data used to calculate Torque, Energy and Power values*

Area of the blades (S) was calculated to be 4.180E-4 m^2.

What we know before actually doing the AI test is:

Diameter (2r) of the pot is of 203 mm and length (l) of 229 mm respectively. Abrasion index tester pot will revolve for 12000 revolutions (θ), at 1470 revolution per minute (rpm) (N).

$$\omega = \frac{2\Pi}{60} \times 1470 = 153.94\ rad\ s^{-1} \quad \text{(B19)}$$

$$\theta = 12000 \times 2\Pi\ rad \quad \text{(B20)}$$

In order calculate the utilized power, torque had to be calculated. This is done by first calculating I, which is given by:

$$\tau = Fr \quad \text{(B21)}$$

Where F and r are force and radius respectively

By definition force is mass multiplied by perpendicular acceleration, given by:

$$F = ma_{\perp} \quad \text{(B22)}$$

Substituting B22 into B21, B21 reduces to:

$$\tau = ma_{\perp}r \quad \text{(B23)}$$

2kg of coal size to -1470+850 micron was used as a test sample.

$$a_{\perp} = \alpha_{\perp} \times r = 0.273\ m\ s^{-2} \quad \text{(B24)}$$

By substituting 2kg and A6 torque (τ) was calculated to be 0.058.

Another formula used to calculate torque is:

$$\tau = I\alpha \quad \text{(B25)}$$

Comparing B 25 and B23, it is evident that I can be obtained, which was found to be 21 kg m^2.

This meaning gyration radius (k) equal 10.5 m, evaluated using: $I = mk^2$ (B26)

Using Formula B6, it is evident that by integration techniques average integral value of torque (Nm) can be obtained. The values reported in Table 14, Pp. 76 was found using the following times (s) recorded using a stop watch:

Table B2: Time intervals

Coal name	Time (s)
Coal A	479
Coal B	465
Coal C	483
Coal D	477
Coal E	486

Table B2 reports time intervals used to calculate the average integral value of torque (Nm). Stop watch was used to record the time intervals. A mill came to rest far quicker when Coal B was ground; it took it long when Coal C was ground.

B.5. Data used to calculate values reported in Table 15

Intensity of abrasion (IA_i) was calculated using Formula B9 and data reported in Table B1; average values of ΔM values, Table B2 and the S value. Wear resistance (WR_i) was calculated using data in Table 14 (Energy values) and Table B1; average values of ΔM values. Work index (W_i) was calculated using energy values in Table 14 and Table 13 (-75 micron weight), which was substituted into B10 to get W_i. Similarly index of comminution (IC) was calculated data reported in Table's 13 (-75 micron) and 14.

Appendix C: Multilinear regression analysis

Table C1: Matrix table used to code in Matlab and Linest

AI (Y)	X1 MT	X2 HGI	X3 Vitri	X4 Inert	X5 EM	X6 IM	X7 TM	X8 Inter	X9 Carbo	X10 X-QM	X11 P-QM	X12 X-Py	X13 P-Py
87.4	6.4	61	15.2	63.2	8	10	20	11.8	5.6	12	7.8	1.3	5.2
115.6	10.5	50	31	43.8	10.6	12	30.8	9.6	4.4	18.0	3.6	1.1	3.2
28.6	4.3	51	7	74.4	0.6	5.8	13.6	9.4	5.6	7.8	4.4	0.9	1.4
85.7	4	52	9.4	57	9.2	20.8	20.8	8.6	0.6	14.3	6.4	0.5	1.2
51.2	4.8	50	14.2	64.2	7	10	16.8	11.8	5.2	7.2	35	1.6	3.8

Note: MT=total moisture, HGI=Hardgrove Grindability Index, Vitri=vitrinite, Inert=inertinite, EM=excluded minerals, IM=included minerals, TM=total minerals, Inter=intermediate microlithotypes, Carbo=Carbominerite, X-QM=X-ray diffraction quantified quartz minerals, P-QM=Petrography reported minerals, X-Py=X-ray diffraction quantified pyrite mineral, and P-Py=Petrography reported minerals

The matrix table was used in Matlab to solve for the coefficients of equation (1). Note that same results (coefficient estimates) were obtained when both Matlab and Linest were used.

Matlab coding

```
x1=[6.4 10.5 4.3 4.0 4.8]';

x2=[61.0 50.0 51.0 52.0 50.0]';

x3=[15.2 31.0 7.0 9.4 14.2]';

x4=[63.2 43.8 74.4 57.0 64.2]';

x5=[8.0 10.6 0.6 9.2 7.0]';

x6=[10.0 12.0 5.8 20.8 10.0]';

x8=[11.8 9.6 9.4 8.6 11.8]';

x9=[5.6 4.4 5.6 0.6 5.2]';

x10=[12.0 18.0 7.8 14.3 7.2]';

x11=[7.8 3.6 4.4 6.4 35]';

x12=[1.3 1.1 0.9 0.5 1.6]';

x13=[5.2 3.2 1.4 1.2 3.8]';

y=[87.4 115.6 28.6 85.7 51.2]';

X=[ones(size(x1)) x1 x2 x3 x4 x5 x6 x7 x8 x9 x10 x11 x12 x13];

a=X\y
```

X is a matrix of independent variables matrix, $x_{n\,(1-13)}$ are independent variables, y are dependent known variables, and "a" are the coefficients we are trying to evaluate such that a general linear equation is defined.

Table C2: Statistical results of Linest regression analysis

ANOVA-LINEST

	df	*SS*	*MS*
Regression	13	31786.01	2445.077692
Residual	4294967295	0	0
Total	4294967308	31786.01	2445.077692

Note: df=degree of freedom and ss=sum of the square of regression.

Table C2 shows the statistical information on how Linest program got to solving the general equation as defined in Chapter 4, Section 4.11.

Table C3: Anova Linest Data generated by computer

Coefficients	*Lower 95%*	*Upper 95%*	*Lower 97.0%*	*Upper 97.0%*
Intercept	0	#N/A	#N/A	#N/A	#N/A
X1 ™	0	0	0	0	0
X2 (HGI)	2.446171818	2.446171818	2.446171818	2.446171818	2.446171818
X3 (Vitrinite)	1.327852189	1.327852189	1.327852189	1.327852189	1.327852189
X4 (Inertinite)	-1.534525653	-1.534525653	-1.534525653	-1.534525653	-1.534525653
X5 (EM)	0	0	0	0	0
X6 (IM or Carbomine)	1.682600733	1.682600733	1.682600733	1.682600733	1.682600733
X7 (T Mine)	0	0	0	0	0
X8 (Intermediates)	0	0	0	0	0
X9 (Carbonates)	0	0	0	0	0
X10 (X-QM)	0	0	0	0	0
X11(P-QM)	-0.236387212	-0.236387212	-0.236387212	-0.236387212	-0.236387212
X12(X-Py)	0	0	0	0	0

X13(P-Py)	0	0	0	0	0

Table C4: Linest data output

RESIDUAL OUTPUT

Observation	*Predicted AI (Y-Axis)*	*Residuals*	*Standard Residuals*
1	87.4	-1.42109E-14	-19703.94966
2	115.6	0	0
3	28.6	3.19744E-14	44333.88674
4	85.7	2.84217E-14	39407.89933
5	51.2	1.42109E-14	19703.94966

Standard error refers to the amount by which an observed value differs from the expected value. Residuals are deviations of the dependent variables from the fitted function. Residual or fitting error is an observable estimate of the observable statistics. What the data in Table C4, which is the statistical output data of Linest, is showing is: the difference between the experimental data and computer generated Y values are so close such that the difference may be in significant.