



The effect of breakage top size and mode on coal liberation

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Abstract

Coal from the Waterberg coalfield is seen as a potential replacement for the depleting Mpumalanga province coal resources. The Waterberg coalfield contains about 40-50% of South Africa's remaining coal reserves and the coal seams are highly intercalated with carbonaceous mudstones. Coal from this region is used to supply local power stations for electricity generation, semi-soft and metallurgical coal for other industries. However, this coal is associated with high ash and high volatile matter that necessitates the need for beneficiation to improve the coal grade. Comminution is a size reduction method that is used to liberate coal macerals from the gangue. Particles must be reduced to the optimal size that will improve the coal quality. Determining the optimal particle top size makes coal mining and processing economical for coal producers. Crushing to excessively small sizes may lead to the generation of fines that are difficult to handle and may require specialised equipment and wet beneficiation methods, rendering the process uneconomical.

To determine the optimal particle top size for liberation and/or for further retreatment, densimetric analysis techniques are employed. However, traditional densimetric analysis methods are time consuming, laborious and employ hazardous chemicals. Due to evolving technological minerals processing environment and the need for environment friendly and rapid sample processing technology, Debtech (now De Beers Group Ignite) designed and manufactured the RhoVol densimetric analyser. The RhoVol densimetric analyser is a 3D image processing densimetric apparatus that weighs and takes measurements of individual ore samples using a series of cameras placed at different angles to determine their volume, mass and densities. Studies have shown that the RhoVol densimetric analyser may be used for densimetric analysis without the need for float-and-sink analysis (Bothloko, 2023). However, the RhoVol densimetric analyser is unable to capture hidden cavities of porous ore particles and therefore tends to overestimate the volume of particles. As such, a density correction factor is required.

In this study, the effect of breakage mode and top size on coal liberation was investigated using the RhoVol densimetric analyser. Proximate analysis was done to determine the ash, moisture, fixed carbon and volatile matter content of the coal. The breakage modes investigated in this study are compressive and impact crushing. Compressive breakage was performed by applying a compressive force using a custom-built 80 kg rudimentary lawn roller over the coal particles. The coal particles were contained within a steel frame of different heights to obtain the desired top sizes. Impact breakage was performed using a drop weight impact rig. The coal particles were placed at the bottom of the drop weight impact rig with steel

stopper rings at different sizes to obtain the required top size. The top sizes investigated in this study were 12 mm, 8 mm, 6 mm, 4 mm and 3 mm. The ideal top size to optimize the yield of low-density clean coal products ($RD < 1.4$) was the focus of this investigation due to the increase in the demand for high-quality coal (grade A/export coal). A helium gas pycnometer was used to determine the true (skeletal) density of the particles to calibrate the RhoVol data. One of the advantages of using the RhoVol densimetric analyser is its ability to provide additional information such as the particle compactness, elongation and flatness. As such, the effect of the breakage mode and top size on particle shape was also investigated.

Proximate analysis of the 16 mm head sample indicates the low quality of the Waterberg coalfield coal, reflected by its high ash (60%) and mineral matter content. The high ash and mineral matter contents necessitate the need for beneficiation of the coal. The analysed data from the RhoVol and pycnometer was used to measure the washability properties of the coal at different top sizes. Results show that compressive breakage of the head sample to top size of 12 mm did not have any significant effect on the liberation of low RD clean coal products ($RD < 1.4$). However, impact breakage resulted in a small improvement of about 1.7% (by mass) in the proportion low-density coal. These particles are composed of vitrinite-rich coal macerals with little mineral matter. When the particles top sizes were further reduced from 12 to 8 mm, the proportion and of the low-density clean coal products ($RD < 1.4$) for both impact and compression breakage modes was significantly improved. About 3.2% (by mass) of clean coal products were obtained after compressive breakage to top size 8 mm as compared to the 6.4% (by mass) achieved through impact crushing. Further size reduction from 8 to 6 mm resulted in a small increase in the cumulative mass yield of low density ($R < 1.4$) materials for both modes. Results show that between the RD intervals 1.2–1.4, there is a small difference in the mass yields of clean coal products ($RD < 1.4$) obtained through compressive and impact breakage respectively when the top size was reduced from 8 to 6 mm. Reducing the top size from 6 to 4 mm did not have any significant effect to the mass yield of low-density products ($RD < 1.4$) after compressive breakage, but a small increase in the mass yield was observed for impact breakage. Crushing down to a top size of 3 mm improved coal liberation for both modes. After every particle top size reduction stage to smaller sizes, the proportion of middlings and high-density coal products decreased.

Coal washability curves show that compressive breakage to top size 12 mm had little effect on the mass yield of clean coal products as compared to the 5.7% low-density clean coal yield obtained after impact crushing. Compressive breakage to top size 8 mm significantly improved the mass yield of low-density clean coal products (at RD cutpoint 1.4) from 0.3% to 14.4%. Impact breakage to top size 8 mm significantly improved the yield of low-density clean coal

products from 5.7% to 18%. Compressive breakage to top size 6 mm improved the mass yield of clean coal products to 21.6% as compared to 21.1% obtained after impact breakage. There were progressive but small improvements in the mass yield of clean coal products when the coal was crushed to top sizes 4 mm and 3 mm. Compressive and impact breakage to top size 3 mm resulted in the highest coal yield at 31.3% and 31.4% (at RD cutpoint 1.4) respectively. However, crushing to smaller top sizes (3 mm) can lead to excessive fines generation that can offset the benefits of the improved liberation.

Cumulative mass yield trends show that the yield of the middlings products between RD interval 1.4-1.8 decreases with the reduction in the particles top size. Compared to the head sample (16 mm), impact breakage to top size reduction to 3 mm decreased the middlings fraction from 60-45%. The mass yield of the middlings products was reduced from 60-50%. Compressive breakage of the 16 mm head sample to 3 mm decreased the mass yield of high-density coal products decreased from 40-18% as compared to 40-20% yield obtained after impact breakage.

Particles top size reduction to smaller sizes liberated more of the lower density clean coal material and improved their mass yield. Crushing 8 mm, 6 mm, 4 mm and 3 mm yielded approximately 25-35% of the low-density clean coal products as compared to 5% attained after impact breakage to 12 mm. As particle top size decreases (6 mm, 4 mm, 3 mm), the difference between compressive and impact crushing is reduced, indicating that the crushing method has less influence on the yield of low-density clean coal yield at finer sizes. Assuming a density cutpoint of 1.4, impact breakage resulted in the highest coal mass yields at top sizes 12 mm, 8 mm and 4 mm. There are negligible differences in the mass yield of compressive and impact crushed coal at top size 6 mm and 3 mm. Significant low-density clean coal yields were reported when the coal was crushed to between 8 mm and 6 mm. To maximize the recovery of low-density clean coal without necessarily generating excessive fines, coal from the Waterberg coalfield should ideally be crushed to between 8- and 6-mm. However, the optimal size would also rely on plant economics, costs related to fines management, and downstream processing. These findings highlight how important top size and breaking mode are to maximizing yield during coal beneficiation.

When the effect of breakage mode and top size on the particle shape was investigated, results show that head sample is mainly composed of compact, dense and round/spherical particles. Crushing the head sample to top size 12 mm via compressive and impact breakage resulted in a shift in the mass distribution of the particles from the most compact, rounder to mid-compact particles. Further size reduction from 12 to 8 mm shows an increased shift in the mass distribution from rounder to irregular and flat particle shapes. The continued shift from

spherical to irregular and flat particles was also observed when the top size was further reduced to 6 mm. The frequency of flat particle in the compactness range 0.42 – 0.51 increased from 6.8% to 8.1% after compressive breakage to 6 mm and from 7.5% to 9.1% in the case of impact crushing. Crushing to top size 4 and 3 mm further increased the frequency of particles from spherical to irregular and flat shapes. Crushing to smaller top sizes increased the frequency percentage of flat particles and reduced the amount spherical and irregular particles.

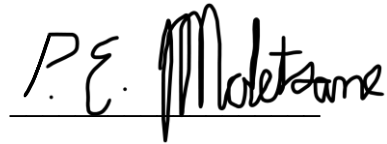
For both breaking modes, crushing to smaller top sizes improved the mass yields of low-density clean coal products. The proportion of spherical dense coal particles was reduced with a decrease in the particle top size. Coal liberation was improved when the coal was crushed to smaller, irregular and flat particles. Compared to compressive breakage, impact breakage was the most effective breakage mode and produced more flat, irregularly shaped particles. The findings from this study show that there is a correlation between the breakage mode, top size and particle shape regarding the coal yield. The above findings show that when properly calibrated with pycnometer data, the RhoVol densimetric analyser measurements can be used for rapid densimetric analysis on coal of varying sizes and shape.

Key words: RhoVol, liberation, compressive breakage, impact breakage, coal mass yield.

DECLARATION OF AUTHORSHIP

I, **Phasomane Elija Moletsane**, hereby declare that the dissertation entitled: "Measuring the effect of breakage mode and top size on coal liberation using the RhoVol densimetric analyser", submitted in fulfilment of the requirements for the degree Master of Engineering in Chemical Engineering, is my own work. All other contributors have been indicated clearly and reference in literature was given as necessary. This work has not been previously submitted in pursuit of a degree at any other tertiary institution.

Signed at Potchefstroom on the 11th day of July 2025.

A handwritten signature in black ink, reading "P.E. Moletsane". The signature is written in a cursive style with a horizontal line underneath the first part of the name.

PE Moletsane

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“When the time is right, I, THE LORD, will make it happen”

Isaiah 60:22

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List of Abbreviations

Abbreviation	Description
AD	Air dried
AR	As-received
DAF	Dry-ash free
DB	Dry basis
CV	Calorific value
ML	Degree of mineral liberation
MM	Mineral matter
NCV	Net calorific value
NAR	Net as received
RD	Relative density
ROM	Run-of-mine
RoVr	Reflectance of vitrinite

Nomenclature

Abbreviation	Unit	Description
ρ_{true}	-	Particle's corrected density (using the pycnometer and RhoVol correlation equation) (RD)
ρ_{RhoVol}	-	Underestimated RhoVol (RD) particle density

CHAPTER 1

INTRODUCTION

Chapter 1 gives an overview of the study being undertaken to measure the effect of breakage top size and mode on coal liberation using the Dehtech RhoVol densimetric analyser. Section 1.1. provides a short discussion on the background and motivation for undertaking this study. Section 1.2–1.3. will underline the objectives of the study and the research scope will be discussed in section 1.4.

1.1. Background and motivation

Coal is South Africa's primary energy resource contributing to about 80% of the country's electricity (CSIR, 2023) and around 35.6% of the world's electricity supply (Ritchie and Rosado, 2020). South Africa contributes around 3.9% of the world's coal production (Makgetla and Patel, 2021) and around 30% of the country's coal is exported to the international markets (McSweeney and Timperley, 2018) with some reports suggesting that under 59 million tonnes (Mt) was shipped overseas as of 2021 (IEEFA, 2022). 2.3% of the nation's Gross Domestic Product (GDP) is attributed to coal mining with between 40-45% of the sales revenue credited to the export of coal to overseas markets (Chamber of Mines, 2018; IEEFA, 2019). Although coal is mainly used for electricity generation in South Africa, it is also used locally in other industrial processes such as the metallurgical sector (Arcelor-Mittal), petrochemicals (Sasol) for coal-to-liquid-fuel (CTL) production and for domestic heating and cooking (Eskom, 2021). Coal is likely to prevail as the principal energy resource in South Africa for a number of years due to its abundant nature and affordability (Jeffrey, 2005b; Hancox & Götz, 2014, Eskom, 2021)

The reliance on coal for power generation is expected to increase as South Africa is facing an energy crisis with rolling blackouts and higher stages of load shedding forcing the government to declare the problem as a National State of Disaster (South Africa government gazette, 2023). South Africa reportedly also plans on extending the life of its ageing coal power stations to tackle the energy crisis, further increasing the country's dependency on coal for power generation (Swilling, 2023). The country's energy demands will likely increase with an increase in population and the Gross Domestic Product (GDP). According to the Integrated Resource Plan (IRP 2019), South Africa's average electricity demand with a projected GDP growth of 3.18% by 2030 is expected to increase by 2% by 2030 and 1.66% by 2050 and in the worst-case scenario at a low GDP growth of about 1.33%, the average energy demands are

estimated to increase by 1.21% in 2030 and 1.24% in 2050 (IRP, 2019). Figure 1.1 summarises South Africa's expected electricity demand forecast to 2050. The graph was "adjusted to show the lower actual-2018 demand as the starting point" (IRP, 2019). The world's dependency on coal for power generation is also expected to increase largely in developing countries. The World coal Association estimates that 22% of the world's energy generation in 2040 will come from coal sources (world coal association, 2023). It is also expected that by 2030 about 53% of developing countries' energy would come from coal (WEC, 2003).

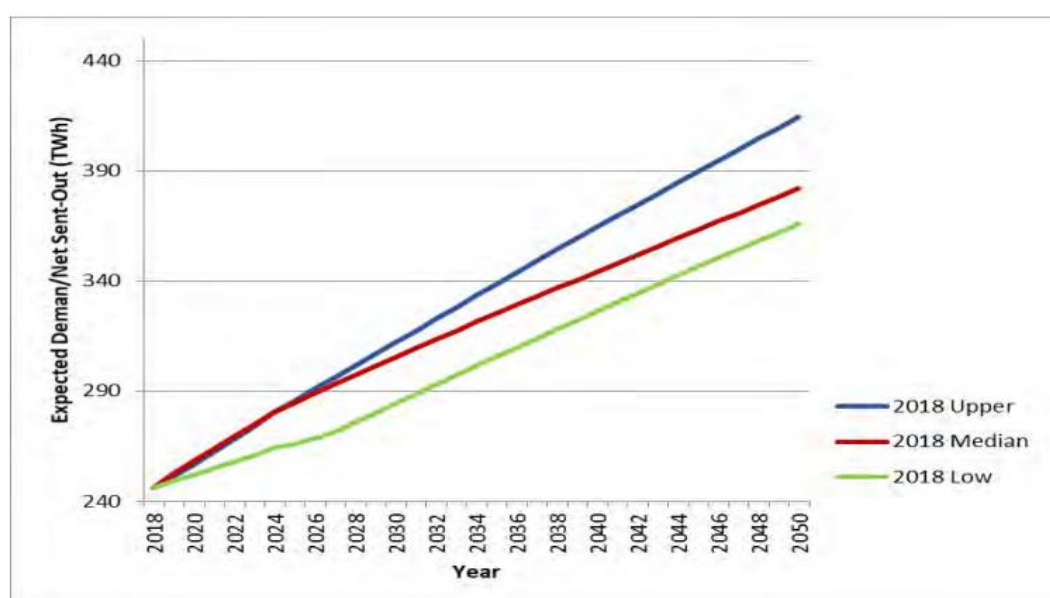


Figure 1.1: Expected electricity demand forecast to 2050 (adapted from the IRP 2019)

The demand for South Africa's coal for the export market has also sharply increased mainly from European countries. The increase in demand is likely due to the ban and sanctions on Russia's energy sources, forcing certain European countries to reopen some of their old fossil fuelled power stations and secure coal supplies from countries such as South Africa (Neely and Dunn, 2023; Fokuhl and Gillespie, 2022). It was reported that coal exports from South Africa to the European union increased by five times between January to September 2022 with some European countries buying over 40% more coal from South Africa in the first quarter of 2022 than what they bought in their entire year of 2021 (Roussanoglou, 2022; Reid and Banya, 2022). Figure 1.2 shows a graphical representation of coal exports from South Africa as compared to other countries as of 2019 (Statista, 2021). Figure 1.3 shows South Africa's coal exports to different countries around the world. Although there has been increased interest in South Africa's coal from the international market, recently, the country's main coal export terminal, the Richards Bay Coal Terminal (RBCT) has reported a 6.2% year-on-year

decline in coal exports due to infrastructure challenges and a shortage of locomotives and spares (Banya and Peyton, 2024).

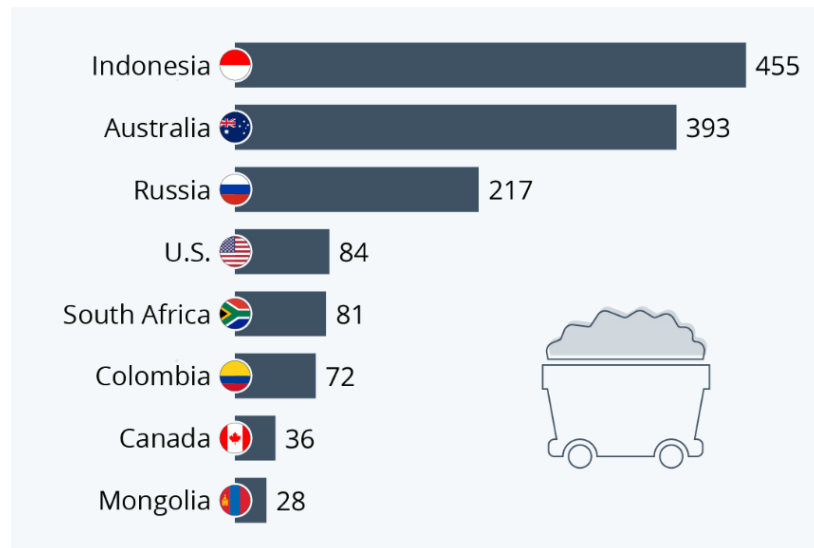


Figure 1.2: World's biggest coal exporters (adapted from Statista, 2021)

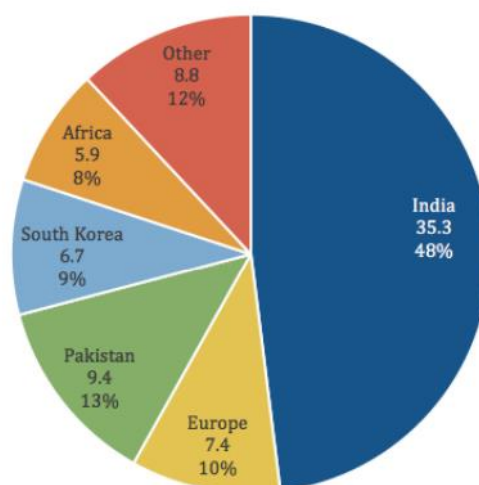


Figure 1.3: Coal exports out of Richards Bay Coal Terminal (Mt) (Adapted from the IEEFA, 2019)

South Africa's abundant coal resources are found in the country's northern and eastern parts, with estimated coal reserves of about 66.7 billion tons (Hancox *et al*, 2014; Department of Energy, 2016). The world's proven recoverable coal reserves are about 1.161 billion tonnes (EIA, 2022) with approximately 9.9 billion metric tonnes of these proven coal reserves left in South Africa (Statistic SA, 2015; Galal, 2023). South Africa's proven coal reserves are mainly

dominated by bituminous coal (about 95%), 2% anthracite and about 2% metallurgical/coking coal (Eberhard, 2011). In South Africa, there are nineteen (19) coalfields mainly situated in the provinces of Mpumalanga, Limpopo, Free State and KwaZulu-Natal with fewer deposits in Gauteng, Eastern Cape and the North-West Province (Jeffrey *et al.*, 2014). Mpumalanga province contributes over 84% of the country's coal production (Mining Weekly, 2010). However, due to depleting coal reserves of the Mpumalanga's coalfield such as the Witbank, Highveld and Ermelo coalfields which have been mined extensively over the years, the Waterberg coalfield is seen as a potential replacement of these coalfields (Jeffrey, 2005a; Jeffrey, 2005b).

Viewed as an important coal source in South Africa, coal from the Waterberg coalfield situated in Limpopo will be used for the purpose of this study. The Waterberg coalfield is composed of 2 Ecca group coal bearing seams termed the Vryheid and Grooteveld formations (Hancox and Götz, 2014). Information on the geology and the quality of coal in the Vryheid and Grooteveld formations will be given in chapter 2. The Grooteveld formation, which is composed of thick interbedded coal-mudstones, yields the highest percentage off run-of-mine (ROM) coal (Faure *et al.*, 1996; Cairncross, 2001; Jeffrey, 2005a; Dreyer, 2011). However, run-off-mine (ROM) coal from this formation has an ash content of between 50 – 60% and volatile matter of between 30 – 35% and beneficiation is required to improve the coal grade (Dreyer, 2011; Hancox and Götz, 2014; Wagner *et al.*, 2019). Coal from the Waterberg coalfield is of low quality and therefore the coal must be beneficiated to improve the coal grade to meet the standards of local and the competitive export market. The ash content of the export coal grade should not exceed 15% (Eberhard, 2011).

Beneficiation is an important step in the coal preparation process. It is performed to reduce the amount of ash producing minerals resulting in products that meet specifications that are not achievable by screening alone (Deysel, 2015). Coal from the Volksrust formation contains about 60% impurities (Chabedi and Mhlongo, 2018) necessitating the need for beneficiating the raw coal to produce vitrinite rich bright coal suitable as blend coking coal (De Korte 1994, 2010). If left untreated, these impurities/ash producing minerals do not burn during combustion producing an ash by-product. Coal treatment minimises the production of waste by reducing the ash content by over 50%, lowering the sulphur dioxide (SO₂) and CO₂ emissions leading to improved thermal efficiencies (Deysel, 2015). Comminution and physical separation can also be used to treat high ash coal content to reduce impurities and increase the mine's commercial value (Ito *et al.*, 2009). Comminution is a particle size reduction process that promotes the release of valuable minerals from the unwanted matter (Wills and Napier-Munn, 2006).

Liberation is an important stage in the processing of minerals as it employs techniques or processes that promote the release of the valuable mineral from the gangue (Wills and Napier-Muun, 2006). To remove unwanted material from coal, the coal is subjected to size reduction methods using techniques such as crushing, grinding etc. to liberate inorganic impurities from the valuable coal (Dworzanowski, 2013, Groppo, 2017). Size reduction and the subsequent liberation of minerals improves recovery and aids economic benefit (Vizcarra *et al.*, 2010; Gerson and Gonzalo, 2012; Weining *et al.*, 2013). Size reduction techniques may also be used to liberate coal macerals, enabling selective separation of the coal's organic components (Cho and Luckie, 1998). The coal must be reduced to an economically viable particle size that will give high and acceptable yield but not too small to avoid the formation of fines that are expensive to process due to high energy requirements and susceptibility to moisture entrapment (Weining *et al.*, 2013; O'Brien *et al.*, 2011). Comminution and crushing are an energy intensive and expensive process with some estimating that it accounts for 3% of the electricity generated in the world (Deniz, 2013). Therefore, the optimal liberation size allows for optimal maximisation of the plant yield leading to the production of high value product from the run-off-mine (ROM) that can counteract the cost associated with comminution or crushing ensuring economic viability (Potgieter, 2014).

The size crushed coal must be closely controlled to make it suitable for retreatment (Weining *et al.*, 2013). For example, Upper Ecca coal must be crushed to a top size of about 15mm for effective separation in dense mediums process to liberate the coking fraction (Chabedi and Mhlongo, 2018). To determine the optimal top size for liberation and for further retreatment, various analytic methods may be employed. Densimetric analysis is particularly important for the measurement of particle's densities. Traditional densimetric determination is performed using float-and-sink analysis. Float-and-sink analysis however, is time consuming, costly, laborious process that employs toxic chemicals that pose health, safety and environmental challenges (High, 2018). This has prompted the research and development of safe, clean and rapid densimetric determination apparatus such as the Debtech RhoVol densimetric analyser. The RhoVol is a densimetric apparatus that weighs and takes measurements of individual ore samples using a series of cameras placed at different angles for volume determination and a rapid mass weighing compartment to determine particle density (Fofana and Steyn, 2017). In this study, the RhoVol densimetric analyser will be used to measure the effect of breakage mode and top size on coal liberation while preventing the excessive formation of fines.

1.2. Problem statement

Coal from the Waterberg coalfield has a high content of ash producing minerals that are incombustible when ignited and may contribute to the emission of SO_2 and CO_2 . The coal seams of the Waterberg coalfield are heavily interlayered and composed with distinct minerals matter such as mudstone and shale (Wagner *et al.*, 2019). The high ash content and low coal grade makes the coal unusable for some local industrial applications and is unsuitable for exportation. High ash coals also pose significant risk to industrial machinery and may reduce process efficiencies and increased wear and tear on the equipment used. Coal liberation is required to unlock the valuable coal from the unwanted gangue; thus, reducing the ash and mineral matter contents, leading to improved coal grade and yield. The coal yield is dependent on the top crush size used in plants; however, the risk of excessive fines generation emerges by crushing to smaller sizes (O'Brien *et al.*, 2011). In order to determine the optimum liberation top size, the yield in relation to liberation for an acceptable coal standard of a low ash coal product will be investigated using the RhoVol densimetric analyser. Crushing the coal to the best optimal top size can lead to improved coal grade, increase process efficiencies and reduce downtime related to equipment failure.

1.3. Aim and objectives

1.3.1. Aim

The purpose of this study is to measure the effect of compressive and impact breakage and top size on the liberation of Waterberg coalfield coal using the RhoVol densimetric analyser.

1.3.2. Objectives

The primary objective of the research is to study the influence of the different breakage modes and top size on the coal yield using data obtained from the RhoVol densimetric analyser. The densimetric data will be used to determine the optimum top particle size for coal liberation and breakage mode that result in the highest coal yield while avoiding the production of excessive fines. Breakage modes to be studied are:

- Impact breakage
- Compression breakage

Specific objectives of the study are to:

- Determine the ideal top size to maximize the yield of clean coal products ($\text{RD} < 1.4$).

- Determine the optimal particle size with the highest coal yield obtained through impact breakage.
- Determine the optimal particle size with the highest coal yield obtained through compression breakage.
- Compare RhoVol data against true density readings from the pycnometer and calculate the error margin.
- Determine the most effective breakage mode and optimum particle size that resulted in the highest coal yield while minimising the excessive generation of fines.
- Determine the effect of breakage mode and top size on particle shape.

1.4. Scope

The effect of different breakage modes and top size on the liberation of Waterberg coal will be investigated using the RhoVol densimetric analyser. Coal samples will be subjected to either impact or compressive breakage. Densimetric determination will be done on the coal samples at different top sizes using the RhoVol densimeter and a helium gas pycnometer. Due to the RhoVol machine limitations, particles smaller than 3 mm (-3 mm) were not subjected to densimetric separation. The RhoVol densimetric analysis machines used in this study can only process particles within -25 mm to + 3 mm size ranges. Since the degree of fines produced varies greatly depending on the type of comminution process, fines (-3 mm particles) were considered outside of the scope of this study. As a result, fines measurements will not be included in washability calculations and the yield curves obtained are optimistic as they do not consider the proportion of the discarded fines. The RhoVol and pycnometer data will be collated and analysed to determine the effect of breakage modes and top size on the coal yield. The effect of breakage mode and top size on particle shape will also be studied.

1.5. Structure of the dissertation

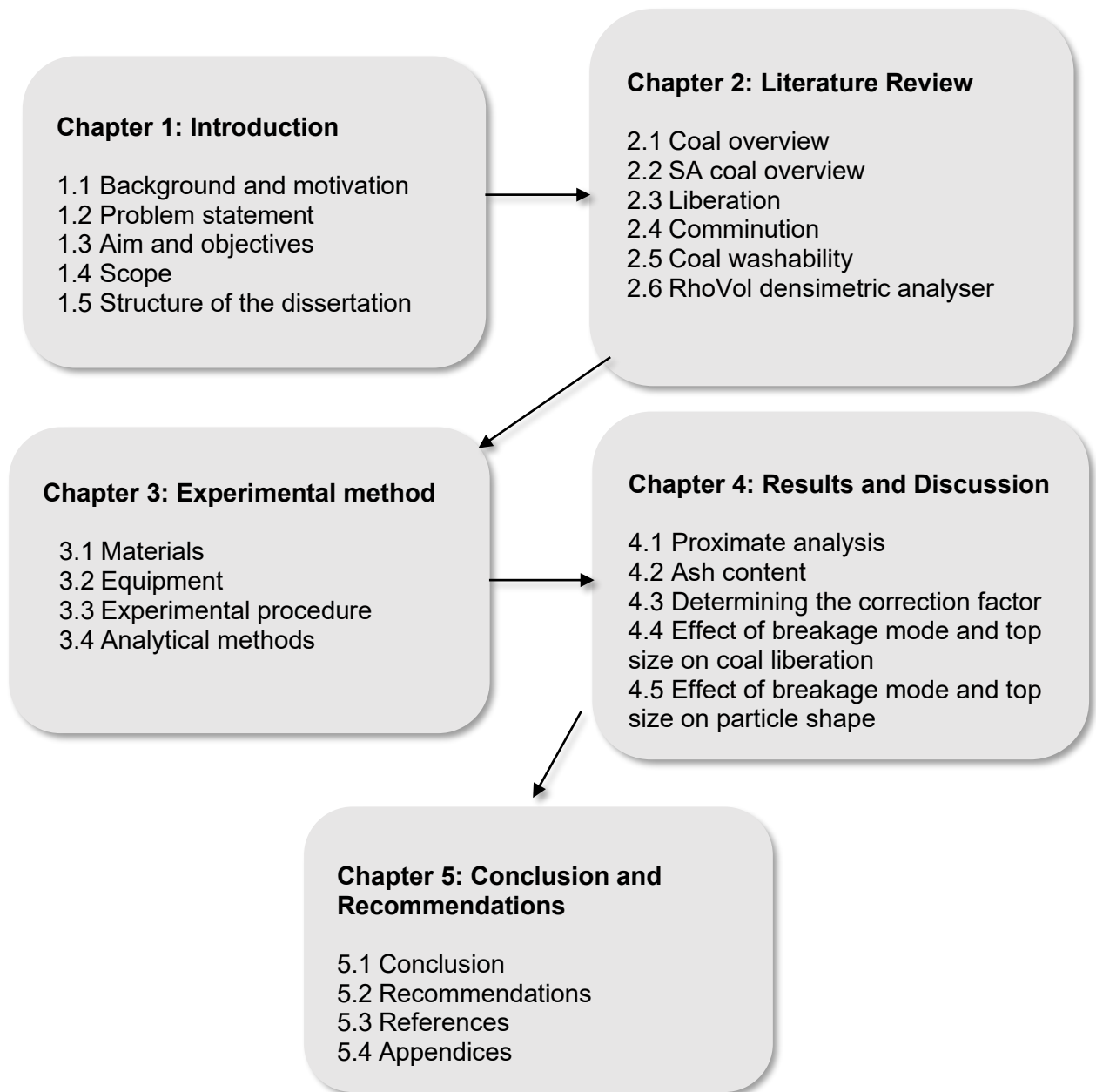


Figure 1.4: Structure of the dissertation

CHAPTER 2

LITERATURE REVIEW

Chapter 2 details and summarises existing and recently published work and topics relevant to this study. In this chapter, a discussion on coal formation and petrology will be given. Discussion(s) on the comminution process, importance of coal liberation and coal beneficiation benefits will be given. The geology and locations of different coalfields in South Africa and coal use will be explained further. Coal properties that affect breakage and the RhoVol densimetric method used in this study will be discussed.

2.1 Coal overview

Coal is a combustible rock made up of organic and inorganic matter formed as a result of geological and biological processes on plant remains over time (Orem and Finkelman, 2003; Schweinfurth, 2020). Coal initially begins as loose peat, a product of decomposed plant remains in swampy conditions and over time, under high pressure and high temperature the peat matures and is converted into lignite, sub-bituminous and bituminous coal (Schweinfurth, 2020; Orem and Finkelman, 2003; SACPS, 2015:16; Falcon & Snyman, 1986). The process is known as the coalification of peat (Falcon & Snyman, 1986). The maturity of coal, as a result of metamorphosis of peat converting peat to lignite, sub-bituminous, bituminous and anthracite improves the physical and chemical properties of the coal and thus its rank (Falcon & Snyman, 1986; Orem and Finkelman, 2003; SACPS, 2015; Schweinfurth, 2020). Figure 2.1 shows the coalification, metamorphosis and conversion of peat to lignite, sub-bituminous, bituminous and anthracite. Table 2.1 shows coal types and their parameters. The difference in these coal type(s) is their intrinsic parameters such as the ash, volatile matter, fixed carbon, moisture and energy content which are used to classify coals by rank (ASTM, 2005).

Mastalerz *et al.*, (2011) defines the coal rank as “the measure of the degree of organic metamorphism (coalification) of a coal, ranging from low-rank peat to high-rank meta-anthracite”. The increase in rank increases the fixed carbon and decreases the volatile matter present (ASTM, 2005; Arnold, 2013). These differences distinguish the coal types from each other. Peat is a soft, dark brown matter associated with low carbon and low energy density (Jovanovski *et al.*, 2023). Lignite is a dark brown coal and the lowest rank coal type with low carbon content (65-70%), high moisture, low energy density and is entrenched with largest quantity of ash producing minerals (Wolfson, 2012; Breeze, 2015; Jovanovski *et al.*, 2023). Anthracite is the highest ranked coal associated with high carbon content (Falcon & Snyman,

1986; Pinheiro & Cook, 2005). Bituminous coal is associated with high carbon and low moisture content (Jovanovski *et al.*, 2023). The coal rank can be established using several physical and chemical parameters and no single variable may be applied over the whole range of ranks (Mastalerz *et al.*, 2011).

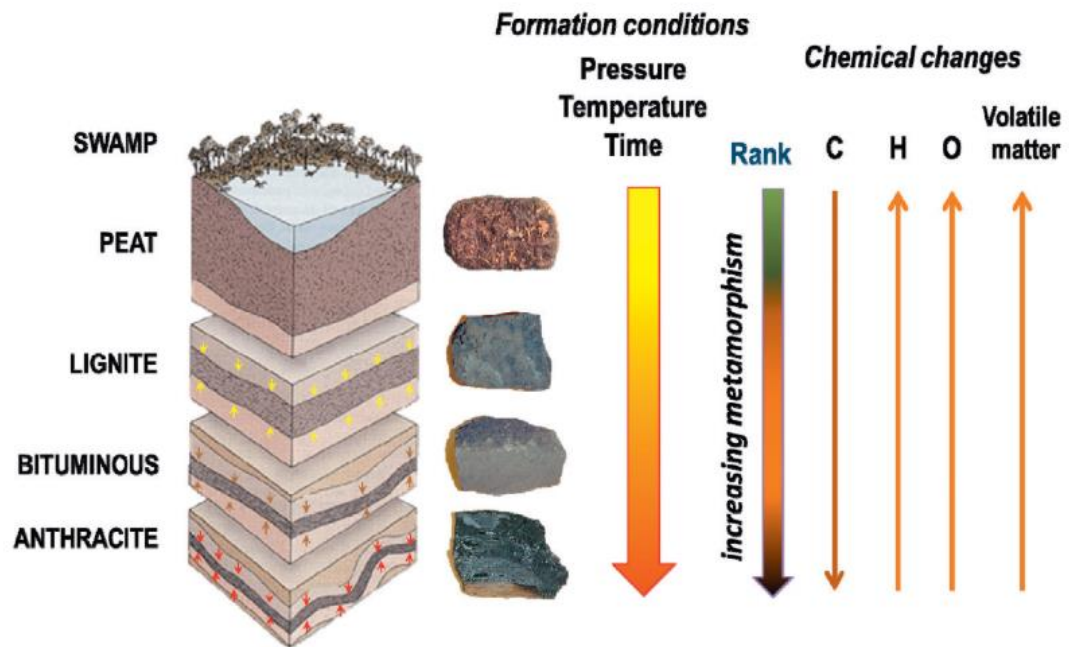


Figure 2.1: Coal formation and coalification process (Pajares and Díez, 2014).

Table 2.1:Types of coal (Breeze, 2015)

Coal types	Dry, carbon content (%)	Moisture content before drying (%)	Dry volatile content (%)	Heat content (MJ/kg)
Anthracite	86-92	7-10	3-14	32-33
Bituminous	76-86	8-18	14-46	23-33
Sub-bituminous	70-76	18-38	42-53	18-23
Lignite	65-70	35-55	53-63	17-18
Peat	< 60	75	63-69	15

Peat is soft coal that may be used as a fuel substitute for firewood for household heating purpose and it can be either crushed or briquetted and used as a fuel for boilers (Kopp, 2024). It can also be used for steam-electric production (Falcon & Snyman, 1986; Kopp, 2024). Lignite is a brown dark coal used almost exclusively for electricity generation (Speight, 2005). Sub-bituminous coal is used mainly for electricity production (Speight, 2005). Bituminous coal is black, and occasionally dark brown dense coal and is used mainly as thermal coal to generate electricity and metallurgical coal (coking coal) for the steel and iron making (Speight, 2005; Sunshine, 2020). Anthracite is hard, brittle black coal predominantly used for heating of residential and business spaces (Speight, 2005) and in the metals industry (Zohuri *et al.*, 2022).

The primary contrast between metallurgical (coking) and thermal coal are their calorific value, volatile matter content, and carbon content (Bell, 2020; Lin, 2023). Thermal coal is used primarily for steam-electricity production and as heating source (Falcon & Snyman, 1986; Speight, 2005) and is associated with low energy density requiring remarkably high air flow for effective combustion (Lin, 2023). Thermal coals are characterised by high volatile matter (10% more than anthracite) and low carbon content (fixed carbon < 90%) (Satyendra, 2018). Coking coal resources are limited and is thus more valuable than thermal coal (Lin, 2023). Coking coal ash content is within the range 8.5-11% (air dried), and the moisture content does not exceed 10% (as received) (Baruya, 2020). The difference between thermal and coking coal is the plastic characteristics during heating as coal melts and swells to produce coke (Baruya, 2020).

2.1.1 Coal organic matter

Organic matter, known as macerals, are mainly composed of elements such as carbon, hydrogen, nitrogen, oxygen and sulphur (Schweinfurth, 2020). Macerals are categorised based on their morphologies and chemical properties and can be differentiated using a microscope (Ping *et al.*, 2024). Macerals are split into three categories namely, vitrinite, liptinite and inertinite (Schweinfurth, 2020). Every maceral group possesses their own distinct physical and chemical characteristics (Falcon and Ham, 1988). Inertinite has the greatest density, followed by vitrinite, with moderate density and lastly liptinite with the lowest density (Ping *et al.*, 2024). The maceral content and rank are fixed for a particular coalfield or coal seam (Malvadkar *et al.*, 2004). A thorough examination of a coal's maceral composition can reveal information about its chemical makeup and how it behaves throughout various conversion processes and can be used as an indicator for coal rank (Pajares and Díez, 2014).

These maceral groups affect the reactivity, hardness, and breakage of coal. According to Esterle (2008), the reactivity of coal is influenced by its macerals' composition. Macerals (organic composition) have an influence on the mechanical strength of coal (Falcon and Falcon, 1987). Additionally, macerals affect how the coal is mined, used and beneficiated (Ping *et al.*, 2024).

Vitrinite is a reactive and combustible maceral (Falcon and Falcon, 1987) formed through the coalification process of huminification, gelification and vitrification (Kumar and Kumar, 2016). Northern hemisphere coals are predominantly composed of high vitrinite content (average 80%) (Falcon and Ham, 1988). Coal deposits from the Free State have a vitrinite content between 5-10% coexisting with high mineral matter content (30-40%) (Stavrakis, 1986; Cadle *et al.*, 1993; Cairncross, 2001). Coals from Kwa Zulu Natal are vitrinite rich with around 60-80% vitrinite, with correspondingly moderately low-ash coals (21%) (Cairncross, 2001).

South African coals are dominated by inertinite maceral and are composed of mineral rich, high carbon, and high ash contents (Falcon and Snyman, 1986; Falcon and Ham, 1988; Wagner *et al.*, 2019). Inertinite is unreactive (combusts slowly) and is dormant in coking (Falcon and Falcon, 1987; Falcon and Ham, 1988). This is due to their limited thermoplastic properties and volatile content (Tillman *et al.*, 2013). Inertinite macerals have the most carbon and lower hydrogen as compared to other macerals at the bituminous coal rank (Ward, 2003; Van Niekerk and Mathews, 2010; Moroeng *et al.*, 2017). South Africa's Highveld coal samples reportedly contain between 68-84 vol% inertinite coinciding with ash content of around 21.6-38.8 wt% (Everson *et al.*, 2013). The RD of inertinite is in the range of 1.35 – 1.70 and it rarely changes with the increase in the coal rank (Falcon & Snyman, 1986).

Liptinite is derived from hydrogen rich resources, waxy and oily plant matter (Falcon, 2013; Ozer *et al.*, 2017). Liptinite macerals are characterised by low reflectance and are mainly aliphatic in molecular structure with low density (Falcon, 2013). Liptinite combusts rapidly (Falcon and Ham, 1988) and constituents in the bituminous C and D coal ranks release hydrogen rich volatile matter and heavy hydrocarbons (Falcon, 2013). Liptinite RD ranges between 1.18 – 1.25 and density varies with an increase in the bituminous coal rank (Falcon & Snyman, 1986).

These macerals all possess different chemical and physical properties that distinguishes them and how the coal is utilised. Vitrinite has adequate plastic and swelling properties and has excellent coking properties while on the contrary inertinite is unreactive and when heated, does not soften (Malvadkar *et al.*, 2004). Liptinite has superior plastic characteristic and is almost entirely distilled as asphaltenes (tar) (Malvadkar *et al.*, 2004). Highveld coal which is predominantly rich in inertinite coupled with an orientated structure is suitable for gasification

and combustion process (Van Niekerk *et al.*, 2008) whereas Waterberg coal with a porous structure and high mineral matter content is mainly used as coking coal or thermal coal for power stations (Megaritis *et al.*, 1999; Cairncross, 2001).

2.1.2. Inorganic matter associated with coal

Coal contains inorganic matter, some of which is assimilated into the organic coal material (Malvadkar *et al.*, 2004). Coal contains between 2-50% volatile matter (Grammelis *et al.*, 2016). The principal band of inorganic matter found in coal include quartz, pyrite, clay and carbonates whereas trace elements are associated with organic matter (Radenovic, 2006; Schweinfurth, 2020). Other inorganic minerals include elements such as iron and zinc primarily used by plants for growth (Schweinfurth, 2020). During combustion, some these minerals are burned and form ash and others such as pyrite can be broken down to form gaseous sulphur oxides (Schweinfurth, 2020). Additionally, coal has free water (inherent moisture) whose content ranges from 40-50% in lignite and less than 5% in anthracite (Malvadkar *et al.*, 2004).

The increase in the coal rank decreases the fraction of trace elements (Radenovic, 2006). Grooteegeluk formation coal is vitrinite rich and is associated with high mineral matter while Vryheid formation coal is inertinite rich contains low mineral matter (Wagner and Tlotleng, 2012). The ROM coal samples of the Waterberg coalfield Grooteegeluk formation reportedly have high ash contents of between 36.6-53.7% whereas the Vryheid formation samples have low ash content of about 10.7% (Wagner and Tlotleng, 2012).

2.2. South Africa coal overview

2.2.1. South Africa's coal

South Africa has an estimated 53 billion tonnes (Bt) of coal reserves, contributing to approximately 7% of the world's coal and is one of the largest five coal producers in the world including the USA, China, India and Japan (Eskom, 2021; Hancox and Götz, 2014). The coal is located in South Africa's Karoo basin in the northern – eastern part of the country (Hancox and Götz, 2014) and date from early Permian period (Cairncross, 2001). Most of the coal was created under steady seismic conditions along with deposits of sandstones and shales from the Ecca formation of the Karoo Supergroup (Snyman, 1998). It has been proposed that the basin is a representative of all coal reserves in southern Africa (Cadle *et al.*, 1993). The coal is mainly high – medium volatile bituminous (Falcon, 1986) and the coal rank increases from west to east (increase in vitrinite content increases the rank) (Cairncross, 2001). Bituminous

coal makes up more than 95% of the country's coal reserves with anthracite contributing to roughly 2% (Kershaw and Taylor, 1992).

There are 19 coalfields in South Africa and about 84% of coal mining activities are concentrated in the Mpumalanga province (Hancox and Götz, 2014; Mining Weekly, 2010) in which twelve of the fifteen (15) Eskom coal-fired power stations are located (Eskom, 2023). The bulk of the coal in the country is mined using surface mining/open cast mines (53%) while underground operations which include board-and-pillar (40%), stoping (4%) and long-wall mining (3%) offset the balance (Eberhard, 2011; Jeffrey *et al.*, 2014). The Highveld, Witbank and Waterberg coalfields hold over 70% of the country's coal reserves (Jeffrey, 2005). The Highveld and Witbank coalfields are the biggest coal producing fields in South Africa (Creamer Media, 2023). Highveld coalfields contain 31% of all coal mines in the country whereas Witbank and Ermelo hold 30% and 13.8% respectively (Deyssel, 2013). Figure 2.2 shows the active and abandoned coal mines in South Africa in their respective coalfields. The Witbank coalfield is near depletion and the Waterberg coalfield is seen as a potential replacement as it contains the bulk of the country's in situ remaining untouched coal reserves (Jeffrey, 2005b).

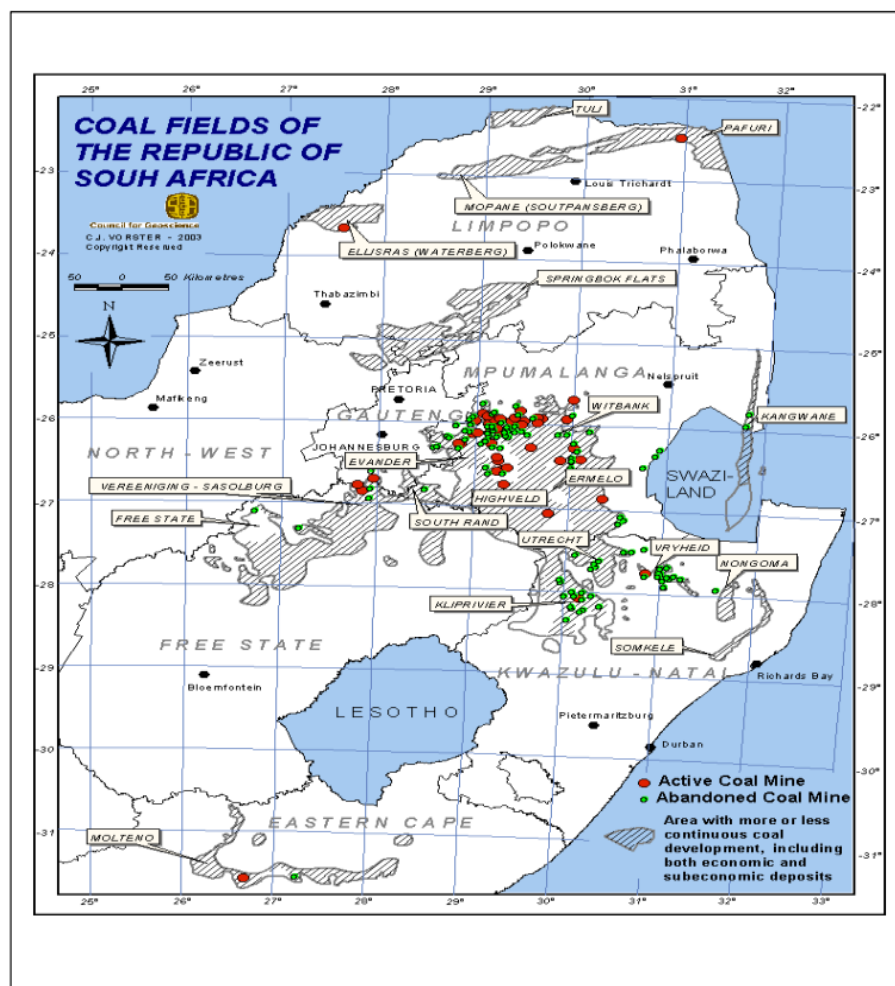


Figure 2.2: South Africa's coalfields with active and abandoned mines (Vorster, 2003)

2.2.2. Uses of coal in South Africa

The majoring of the coal mined in the country is used for power production (Jeffrey, 2005, Eskom, 2021), secondary use being for metallurgical, household and the world's only commercial synthetic fuel production plant (Eskom, 2021, Hancox and Götz, 2014). Around 51% of the coal is extracted through underground mining and the balance (49%) through open cast mining methods (DoE, 2016). Figure 2.3 shows graphic model coal consumption by different sectors in South Africa as of 2021 as per data supplied by Eskom (Eskom, 2021).

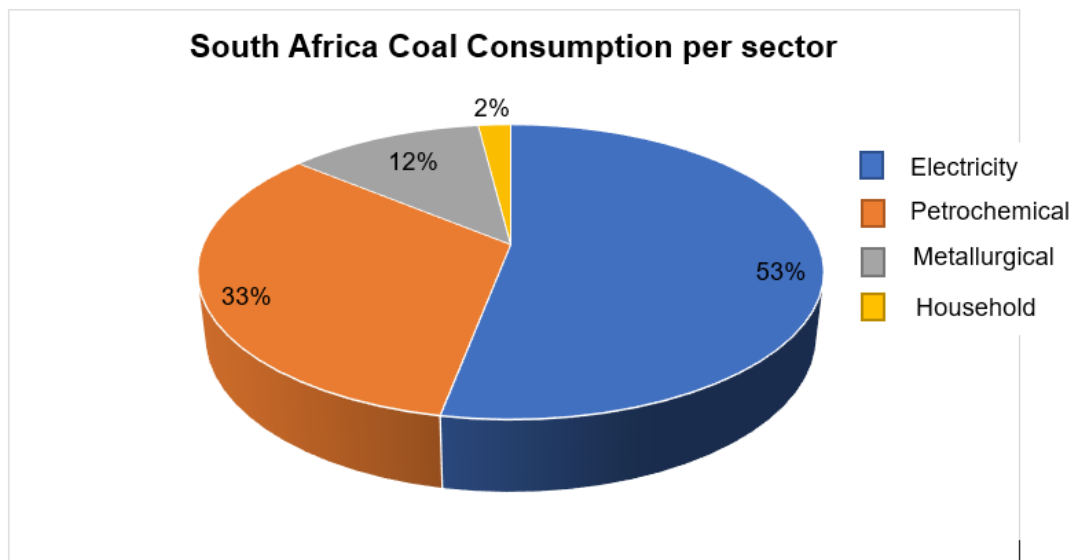


Figure 2.3: South African Coal Consumption (adapted from modified Eskom, 2021)

2.2.3. Waterberg coalfield

Coal from the Waterberg coalfield will be use in this study to investigate the effect of the breakage modes on the coal. A description of the coalfield basin, geology and coal chemistry is explained.

2.2.3.1. Waterberg coalfield reserves and geology

About 40-50% (approx. 50 billion tonnes) of the nation's coal resources are found in the Waterberg coalfield (Hancox and Götz, 2014). The Waterberg coalfield is situated in the

northwestern part of the Limpopo province, in the vicinity of Lephalale and near the Botswana border (Faure *et al.*, 1996; Wagner *et al.*, 2019). The Waterberg coalfield is part of the Eccra group covering an area 360 000ha located in the Ellisras basin (Hancox and Götz, 2014). The Waterberg coalfield falls in the Permian to early Jurassic Karoo-aged Ellisras sub-basin, which is part of the larger Kalahari Basin in neighbouring Botswana (Faure *et al.*, 1996; Cairncross, 2001; Hancox and Götz, 2014). The Ellisras Basin is confined by three faults namely, the Eenzaamheid Zoetfontein and Daarby fault (Jeffrey, 2005a). Figure 2.4 shows the Waterberg coalfield and the location of the Grootegeluk mine and Figure 2.5 illustrates the faults that that confine the Ellisras basin.

The coal seams were deposited about 260 to 190 million years ago in the middle and upper Eccra in the east to west direction whose sediments were laid down after the glacially placed Dwyka deposits (Hancox and Götz, 2014; Wagener *et al.*, 2019). This Eccra group is made up of two main coal bearing formations namely the Grootegeluk and Vryheid formations as shown in Figure 2.6 (Wagener *et al.*, 2019). These coal bearing formations are composed of 11 coal bearing zones of varying quality (Wagener *et al.*, 2019). The Grootegeluk formation is composed of 7 coal bearing zones and the Vryheid formation of 5 coal seams (Hancox and Götz, 2014).

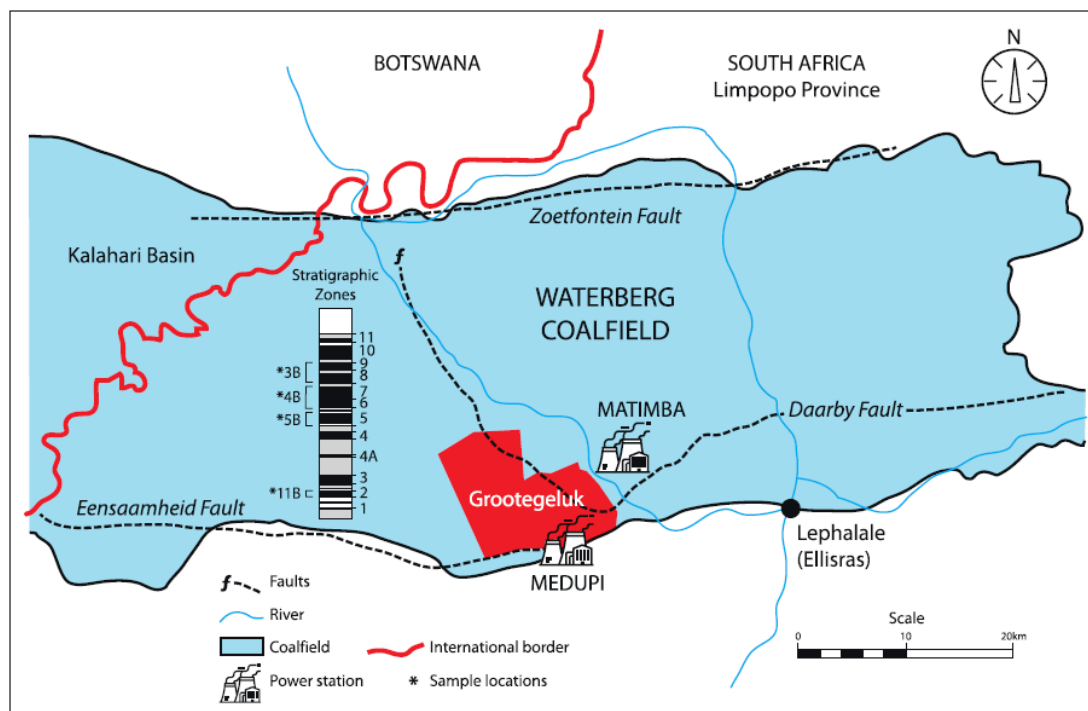


Figure 2.4: Waterberg Coalfield (modified from Baker, 2014)



Figure 2.5: Shallow and Deep coal areas in relation to Grootegeeluk coal mine (GCM) (Jeffrey, 2005a)

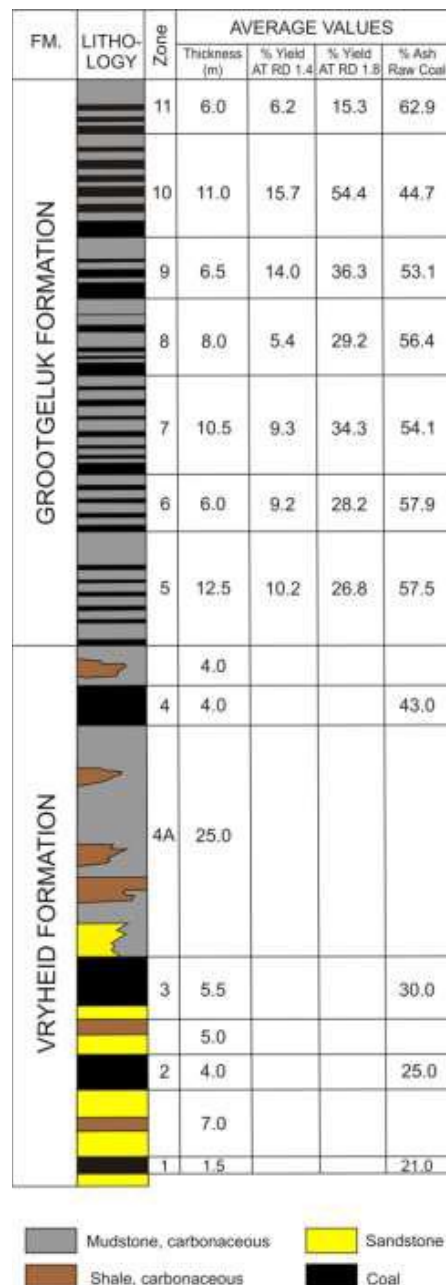


Figure 2.6: Stratigraphic column of the geology of the coal-bearing sequences of the Waterberg Coalfield showing the nature and coal qualities of the 11 coal zones (modified from Hancox and Götz, 2014).

The Grootegeluk formation is between 60 – 90m thick, composed of thin coal seams interbedded with thick carbonaceous mudstones (Jeffrey 200b; Hancox and Götz, 2014). Maceral studies of the coal seams show that the coal is vitrinite rich (up to 90%) with the vitrinite concentration in the formation increases upwards indicating a rise in the depositional environment's energy (Faure *et al.*, 1996). The coal is entrenched with a high quantity of macerals and high concentration of trace element in the run-off-mine (ROM) above global averages (Eroglu, 1992; Wagner and Tlotleng, 2011). The coal zones (5-11) are of similar quality besides zone 5 which has a high phosphorus content and may only be utilized for the

production of steam coal (Hancox and Götz, 2014; Wagner *et al.*, 2019). Zone(s) 6 – 11 produces semi-soft coking coal, power generation and export coal. The ROM coal from this formation has an ash content of between 50 – 60% and volatile matter of between 30 – 35% and beneficiation is required to improve the coal grade (Dreyer, 2011; Hancox and Götz, 2014; Wagner *et al.*, 2019).

The Vryheid formation of the Ellisras sub-basin has a depth of about 15 – 400m and 55m thick composed of mainly of coarse sandstones, carbonaceous mudstones and 5 coal layers of thickness ranging between 1.5 – 9m (Jeffrey, 2005b; Hancox and Götz, 2014). The Vryheid formation is composed of low-quality dull coal of zones 2 – 4 whose coal may be used for metallurgical and electricity production (Hancox and Götz, 2014; Wagner *et al.*, 2019). In the study by Chitlango *et al.*, (2023), they found that Grooteegeluk formation's sink fractions have a relatively high ash output, between 66.4 – 71.2 wt% as compared to that of the Vryheid formation ranging from 58.1 – 65.4 wt%. The existence of mudstones within the Waterberg coalfield coal necessitates the need for higher beneficiation of coals (Jeffrey, 2005a). The Grooteegeluk mine, is one of the biggest coal mines in the country and it supplies coal to Eskom's Matimba and Medupi power station and as well soft coking coal to steel manufacturer Mittal (Exxaro, 2022).

2.2.3.2. Beneficiation of Waterberg coalfield coal

Dense medium separation (DMS) is a common beneficiation method used in South Africa's coal handling and preparation facilities (Bergh *et al.*, 2013). DMS is employed in coal preparation to separate clean coal from the gangue or high-ash coal to produce a commercially graded final product (Wills and Napier-Munn, 2006). In DMS, particles are separated according to their relative density (RD). In coal, the gangue matter is comprised of dense (heavy) material in the RD range of 2.5 and higher, while the organic components are the lighter particles in the range of 1.3 to 1.7 (Bergh *et al.*, 2013). Coal products with RD ranging from 1.4-1.8 represents the middlings and is composed of coal macerals and mineral matter (Potgieter, 2017). Clean coal is a low-density coal product of RD <1.4 (between 1.2-1.4) and is predominantly composed of pure coal macerals and very low mineral matter content (Speight, 2005; Potgieter, 2017). This coal can be used locally in metallurgical process that require specific coal products such as coking coal or could be sold internationally (export coal) where there is a demand for high quality, low-ash coal. These coal categories (low-density clean coal, middlings and high density/dense coal) will be helpful in understanding the significance of the impact of liberation at different top sizes.

Figure 2.7 shows the improvement in the coal yield and potential products obtained after beneficiation of the coal from the Waterberg coalfield. Beneficiation of the Waterberg coal will yield coal of improved quality that is suitable for the export market. The ash content of the export coal grade should not exceed 15% (Eberhard, 2011). Primary beneficiation of the zone(s) 5 – 11 coals may produce excellent medium coking coal with an ash content of around 10.5% whereas secondary cleaning of the coal yields middlings of about 35% ash composition (Hancox and Götz, 2014). In the study by Harrar *et al.*, (2022) it was reported that the tailings fraction obtained after beneficiation were enriched in ash of up to 68.2% whereas the ROM coal sample had lower ash content of 50%. This shows that beneficiation reduced the ash content of the ROM and thus improving the coal grade.

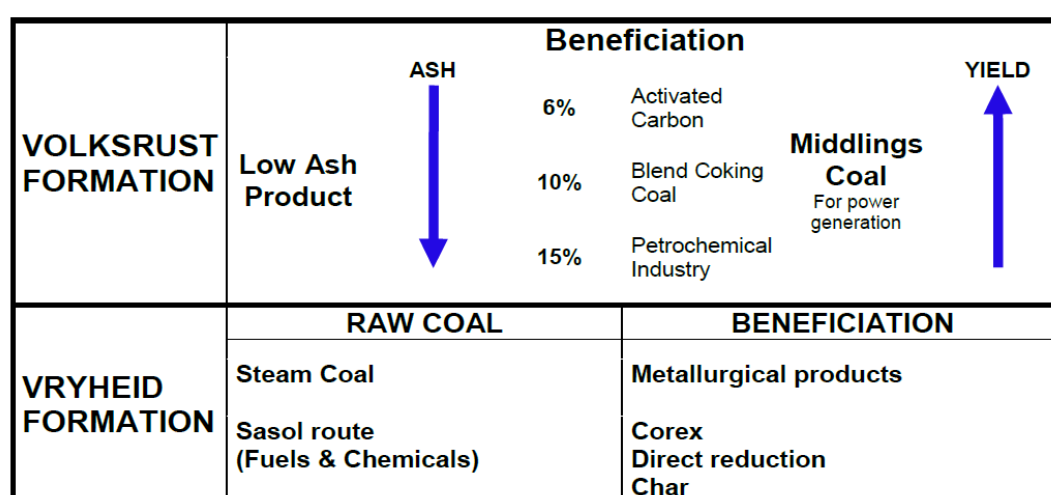


Figure 2.7: Waterberg coalfield potential products (adapted from Dreyer, 2011)

Table 2.2 shows the specification of the different coal products/grades in South Africa. High quality grades A and B coals are referred to as export coals and are shipped overseas or used locally in metallurgical and chemical industries (Steyn and Minnitt, 2010). In South Africa export coal is divided into three categories: namely RB1, RB2 and RB3(RB – Richards Bay) (Steyn and Minnitt, 2010, Bergh *et al.*, 2013). RB1 and RB2 are high quality coals with typical CV ranging between 5 850 to 6 000 kcal/kg and are characterised by their high and moderate volatile matter quantities in their thermal products. RB3 coal is low-grade thermal export coal product of CV below 5 500 kcal/kg NAR (Bergh *et al.*, 2013). In order produce low-grade thermal export coal, beneficiation usually takes place at cut-point RDs beyond 1.7 to 2 (Bergh *et al.*, 2013).

According to Steyn and Minnitt (2010), three thermal coal sized products namely: duff (0 × 6 mm); peas (6 × 25 mm) and small nutts (25 × 40 mm) are consumed locally. South Africa's

thermal coal (steam coal) has a CV ranging from 23 to 28 MJ/kg (Steyn and Minnitt, 2010). For electricity generation, Eskom utilises low rank RB4 coal which is distinguished by its relatively high heat content of about 4 800 kcal/kg (19 MJ/kg) (Deysel, National coal suppliers, 2024). Grade D coal can be utilised as thermal coal as the coal specification for Eskom's power plants require coal products with a CV of 21 MJ/kg (NAR) and ash contents between 25-33%.

Table 2.2 South African coal specifications (Steyn and Minnitt, 2010)

Domestic coal specifications					
Parameter	Units	A grade	B grade	C grade	D grade
Calorific value	MJ /kg ad	>27.5	>26.5	>25.5	>24.5
Total moisture	Maximum	12.0	12.0	8.0	8.0
	% (AR)				
Ash	Maximum	15.0	16.0	18.0	21.0
	% (AR)				
Volatile matter	Minimum	24.0	23.0	23.0	23.0
	% (AR)				
Sulphur	Maximum	1.0	1.0	1.0	1.5
	% (AR)				

2.2.3.3. Waterberg coalfield coal qualities

Proximate and ultimate analysis studies by Makgato and Chirwa (2017) on Waterberg coalfield coal samples received from one of Eskom power station show that the coal ash content ranges between 29-34.5% (wt%), moisture 1.8 – 2.7% (wt%), volatile matter 21-26% (wt%) and measured calorific value of between 20-21% (wt%). Macerals analysis of the coal show that the coal is vitrinite rich (51.8%). Table 2.3 shows the proximate and ultimate analysis of Waterberg coalfield coal samples and Table 2.4 shows the macerals analysis of the Waterberg coalfield coal.

Table 2.3: Proximate Analysis and Ultimate Analysis of Waterberg coalfield coal (modified from Makgato and Chirwa, 2017)

Sample	Carbon (wt.%)	Hydrogen (wt.%)	Nitrogen (wt.%)	Oxygen (wt.%)	Sulphur (wt.%)	Ash (wt.%)	CV (MJ/kg)	Moisture (wt.%)	VM (wt.%)
Sample 1	50.7	3.20	1.10	5.63	1.37	29.0	20.4	2.7	21.4
Sample 2	49.2	2.75	1.22	9.04	1.49	31.3	21.0	2.5	24.0
Sample 3	48.7	2.98	1.12	6.65	1.35	34.5	20.2	2.2	24.9
Sample 4	53.8	3.18	1.14	5.66	1.15	34.8	20.1	2.5	24.8
Sample 5	52.5	3.13	1.14	7.15	1.20	34.2	20.3	2.5	25.7
Sample 6	51.5	2.79	1.58	4.27	1.48	34.0	20.3	1.8	25.6
Sample 7	51.2	3.07	1.18	5.15	1.34	33.4	20.4	2.1	24.6
Sample 8	53.2	3.07	1.11	5.41	1.32	31.0	20.8	2.2	26.2

Table 2.4: Maceral analysis of Waterberg coalfield coal (modified from Makgato and Chirwa, 2017)

Macerals	Value
Vitrinite [vol.%]	51.8
Liptinite/Exinite) [vol.%]	2.9
Reactive Semifusinite [vol.%]	5.3
Total Inertinite [vol.%]	22.6
Visible Minerals [vol.%]	17.5
Mean Reflectance, Ro%	0.76

2.3. Liberation

Coal is usually subjected to washing to remove unwanted minerals or rock to upgrade its value (Sanders, 2007). The process of freeing locked valuable minerals from the unwanted is defined as liberation (Wills & Napier-Munn, 2006; Usaini *et al.*, 2014). The run-of-mine ROM coal may be large in size and contain a blend of organic and non-combustible inorganic matter that affects the quality and lowers the value of coal (Luttrell and Honaker, 2013). Figure 2.8 shows the examples of cross sections of ore particles after comminution. Liberation can be achieved through comminution by employing primary, secondary or tertiary size reduction techniques (Gupta and Yan, 2006) to improve the quality and yield of the ore (Du Plessis, 2010; O'Brien *et al.*, 2011). The reduction of the coal size also makes it easy for transport. Size reduction involves crushing of the ore by either impact or compressive breakage followed by attrition before recovery and use in other processes (Ozean and Benser, 2013, Sahoo *et al.*, 2011, Gupty, 2003).

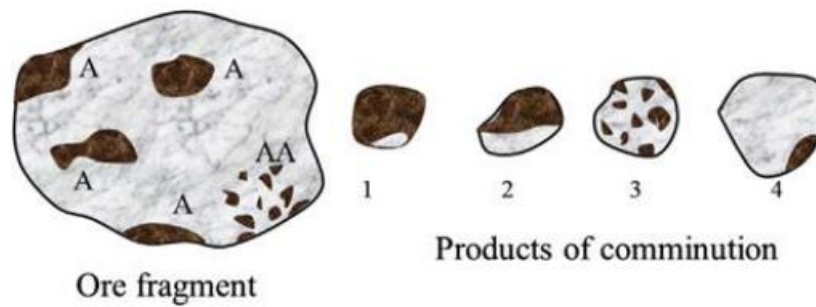


Figure 2.8: Cross section of ore particles after comminution (Wills and Finch, 2016)

Complete liberation, that is the removal of all gangue/ash-forming minerals is not possible (Wills and Finch, 2016). It can be seen in Figure 2.8 of the comminution products that even though complete liberation is not possible, the bulk of the mineral gangue has been removed. The locked gangue particles entrenched in the ore are referred to as middlings and may be further unlocked through comminution (Wills and Finch, 2016). To ensure sufficient liberation where possible, the extent of liberation must be measured or estimated. Wills and Napier-Munn (2006) define the degree of liberation as “the percentage of the mineral occurring as free particles in the ore in relation to the total content”.

Numerous studies have been conducted in the past and different methods to measure the degree of liberation have been proposed. Shahzad and Ali (2018) reviewed previous studies on coal liberation determination and various methods used to estimate coal liberation attributes, i.e. the fractionation method, macroscopic and microscopic methods X-ray computed tomography is another method that may be used to measure liberation however, the technique is expensive, and it is rarely used for commercial applications (Camalan *et al.*, 2017; Zhang and Subasinghe, 2013). Oki *et al.*, (2004) put forward an equation to measure the degree of mineral matter liberation in coal. The equation considers the component of coal before and after combustion and that each component of coal and mineral matter has a different amount of ash, which is found in both as freed coal matter, liberated mineral matter, and trapped particles (Oki *et al.*, 2004). The following equation may be used to determine the degree of mineral matter liberation:

$$\text{ML (\%)} = \frac{\text{Liberated MM}}{\text{MM}} \times 100 \quad (1)$$

ML is the degree of mineral liberation MM is the mineral matter.

Coal liberation is affected by the composition of the mineral matter (Esterle *et al.*, 2002; Shi, 2014) and particle size and shape (Norazirah *et al.*, 2015). Coal should be liberated at the coarsest feasible size as this reduces energy requirements and minimises the production of fines (Wills & Napier-Munn, 2006; O'Brien *et al.*, 2011). Although fine particle size reduction increases the liberation of impurities, it may pollute the content of valuable particles (Yue *et al.*, 2023). Huang *et al.*, (2023) reported that there is insignificant improvement when micro-sizing coals. In this study, the influence of impact and compressive breakage on coal yield will be investigated. Attrition breakage by grinding will not be investigated as this led to micro-sizing and the formation of fines. The two breakage methods are explained further in sections 2.4.3 and 2.4.4.

2.4. Comminution

Comminution is a particle size reduction process that promotes the liberation of valuable minerals from the gangue by employing mechanical or chemical methods (Wills, 1990; Wills, 1997; Drzymala, 2007: 124). The material to be processed is crushed and sorted to the required particle sizes for further processing (Napier-Munn *et al.*, 1996; Eisele *et al.*, 2013). Comminution is a crucial process in an overall beneficiation operation. Comminution processes should be regulated so that the resulting particle sizes are sufficiently large for practical use and to minimise the generation of fines (Weining *et al.*, 2013). Fines are hard to clean and require wet processes that may have negative financial implications (Sahoo and Roach, 2005).

2.4.1. Comminution techniques

2.4.1.1. Mechanical comminution

Mechanical size reduction techniques include crushing and grinding employing equipment such as jaw, gyratory, cone crushers, roll and impact crushers as primary, secondary and tertiary crushing stages and grinding using rod or ball mills, stirred mills or attritors (Wills and Napier-Munn, 2006). Crushing is performed dry (Wills and Napier-Munn, 2006) and the type of equipment chosen is dependent on the size and hardness of the ore (Adeniji, 2018). Primary crushers are used for size reduction of ROM ores as large as 1.5m whereas secondary crushers subsequently reduce primary crusher product with a diameter of less than 15cm to a size suitable for grinding (Wills and Napier-Munn, 2006). When the ore is soft to medium and solely a coarse product is needed, only two steps of crushing are required; however, three

stages are required when the ore is medium to hard and a fine product is needed (Gupta and Yan, 2006).

2.4.2. Particle breakage/loading mechanisms

Particle breakage during comminution occurs as a result of mechanical processes that induce localized or distributed stresses to individual or a bed of particles resulting in breakage (Sehlabaka, 2021). These mechanical processes may be differentiated according to the type of contact made and the trajectory and magnitude of the applied load (Sehlabaka, 2021). Coal breakage occurs when the energy supplied to the coal surpass their intrinsic strength (Esterle, 2008). Depending on how the load is applied, and the nature of contact made, four kinds of particle breakage mechanical processes namely compression, shear, impact and abrasion may occur (Rumpf *et al.*, 1973). Figure 2.9 shows typical loading mechanisms in a comminution setting. Choosing the most suitable particle breakage mechanism is important as the degree of liberation is influenced by the type of breakage mode, which in turn affects the downstream separation stage (Parapari *et al.*, 2020).

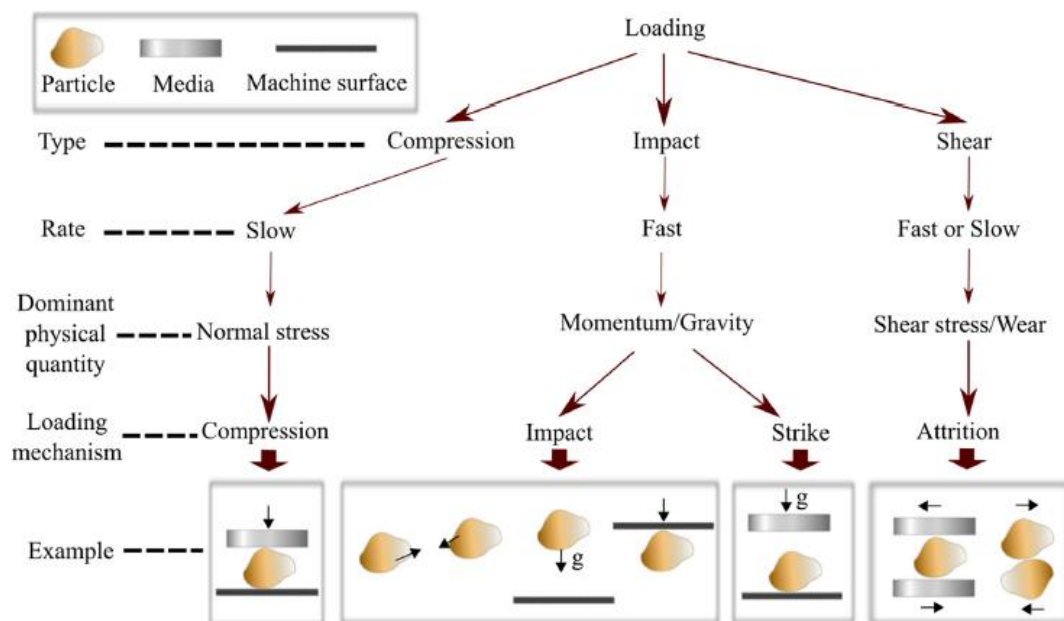


Figure 2.9: Loading mechanisms in a comminution environment (adapted from Parapari *et al.* 2020)

Particles break due to applied stresses by impact and/or pressure induced and in some instances a combination of forces. For instance, compressive forces are applied when grinding brittle solids and some component of shear is also present (Hogg, 2001). In impact mills, breakage is due to direct impact between the particles and the hammer, shearing of large

particles between the hammers and the grate and particles collisions in the mill (Hogg, 2001). Ore properties and the loading mechanism may also have an influence on the type of breakage mechanical processes/crushing methods employed for size reduction purposes (Hogg and Cho, 2000; Little *et al.*, 2016).

There are several factors that affect particle breakage. These include physical properties such as shape, size and texture of the particles; process parameters such as the loading mechanism intensity, temperature, and whether or not comminution is done in wet or dry environment as well as pre-treatment of the ore before comminution (Parapari *et al.*, 2020; Sehlabaka, 2021). Sharp edges may permit the creation of large local stresses (Sehlabaka, 2021). Wet grinding may result in even and polished particle surface (Ahmed, 2010) caused by abrasion and chipping breakage mechanisms (Parapari *et al.*, 2020). On the other hand, dry grinding may result in microstructural defects in samples (Ahmed, 2010) which may be caused by shattering or cleavage breakage (Kaya *et al.*, 2002)

Impact breakage refers to the instantaneous fracture or disintegration of particles by loads due to high impact stresses. Particle breakage testing typically involves dropping a load of known mass from a specified height to determine the amount of energy absorbed by particles when they break. Particle size greatly affects the fracture behaviour of particles as the relative strength required to break smaller particles is more than that needed to break larger particles (Sehlabaka, 2021). Typical comminution equipment includes hammer mills in which falling material is thrust against the plate beaker by hammers (SACPS, 2015:103).

Compression breakage occurs when a particle is subjected to compressive force between two surfaces causing cracking and breakage of the particle (Sehlabaka, 2021). Some studies (Mariano, 2016; Leon, 2018) attributed cleavage breakage to compressive loading mechanism and according to King (2012), this breakage mechanism result in the formation of large and fine particles that emanate from sites of applied force.

2.4.3. Impact breakage

Impact breakage describes the instantaneous, direct impartation of one moving object against another, which may be stationary or moving (SACPS, 2015:90). Kinetic energy is transferred to the ore particles upon contact creating internal stresses large enough to cause fracture (Wills and Napier-Munn, 2006). Particles break immediately upon impartation and there are no residual stresses associated with impact breakage (Wills and Napier-Munn, 2006). There are two categories of impact breakage namely, gravity and dynamic impact. Gravity involves dropping the ore from a defined height onto a solid surface and dynamic impact entails breaking of particles whilst in motion (SACPS, 2015). Free-falling ore is

impacted by a hammer that transfers kinetic to the particles increasing the internal stresses leading to breakage (Wills and Napier-Munn, 2006). Figure 2.10 and Figure 2.11 shows typical equipment used for gravity and dynamic impact breakage. In hammer mills coal particles are continuously hammered until they are small enough to pass through the grid plates (Eisele, 2013). Impactors on the other hand use hammers to crush free falling particles and slam them against hardened plates leading to fracture of the coal particles by the hammers and the plates (Eisele, 2013).

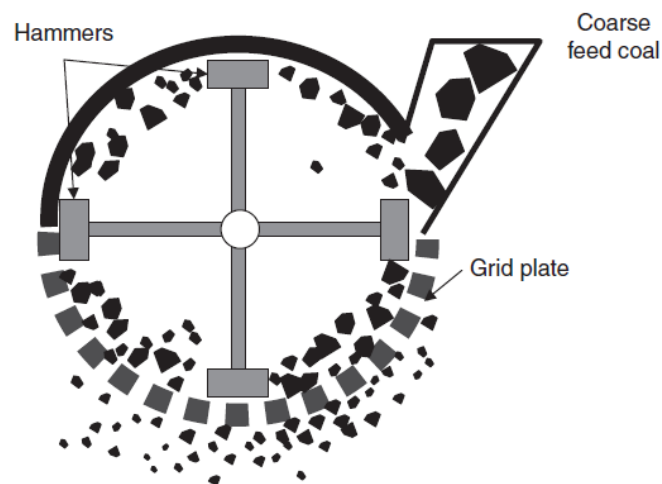


Figure 2.10: Schematic of a hammer mill (Eisele, 2013)

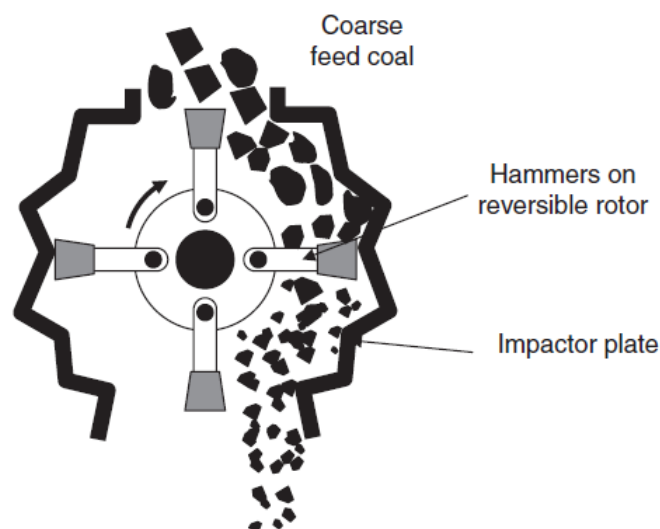


Figure 2.11: Impactor mill (Eisel, 2013)

Impact breakage may also be achieved through grinding by subjecting the ore to abrasion and impact free falling media such as rods, balls or pebbles (Wills and Napier-Munn, 2006). This method uses a combination of impact and abrasion modes to achieve particle reduction.

Crushing to smaller sizes may enhance the overall metallurgical performance particularly for difficult to treat ore (Du Plessis, 2010). However, excessive production of fines especially in coal liberation may occur and is undesirable as fines are difficult to handle and the process increases energy consumption. In the study by Shi *et al.*, (2018), modelling data of high impact breakage show bright layered coal demonstrated a strong size-dependent breakage effect as compared to stone and dull banded coal (C4 and C5). Impact test is used to evaluate the total energy absorbed when particles break.

2.4.4. Compressive breakage

Breakage is achieved by applying a uniform force over the particles crushing the ore between two surfaces. Compressive breakage produces coarse particles as a result of induced tensile failure and fines are generated by pressure failure near loading points (Wills and Napier-Munn, 2006). Coal composition and physical properties affect breakage as shown in studies (Viljoen *et al.*, 2015; Esterle *et al.*, 2002). Internal stresses are present in ore particles subjected to compressive breakage which result in cracking (Wills and Napier-Munn, 2006). Figure 2.12 shows the fracture of an ore particle under compressive crushing. High density ores are hard to break compared to low density (Viljoen *et al.*, 2015). High compressive forces accelerate equipment wear and tear (Gupta *et al.*, 2017) and as such, the force used for liberation should be taken into consideration.

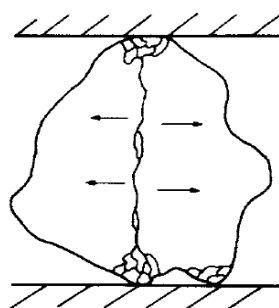


Figure 2.12: Fracture by compressive crushing (Wills and Napier-Munn, 2006)

Typical equipment used for compressive breakage include single and double rolls crushers. Figure 2.13 shows a schematic representation of single and double roll crushers. Roll crushers use shear or compression force by pressing the ore particles against two hardened surfaces

resulting in size reduction (Wills and Napier-Munn, 2006; Eisele, 2013). Particle size influences the breakage mechanism. High compressive forces are required to break coarse particles due to their brittle properties whereas fine particles undergo some sort of plastic deformation necessitating the need for repetitive stress application (Sehlabaka, 2021).

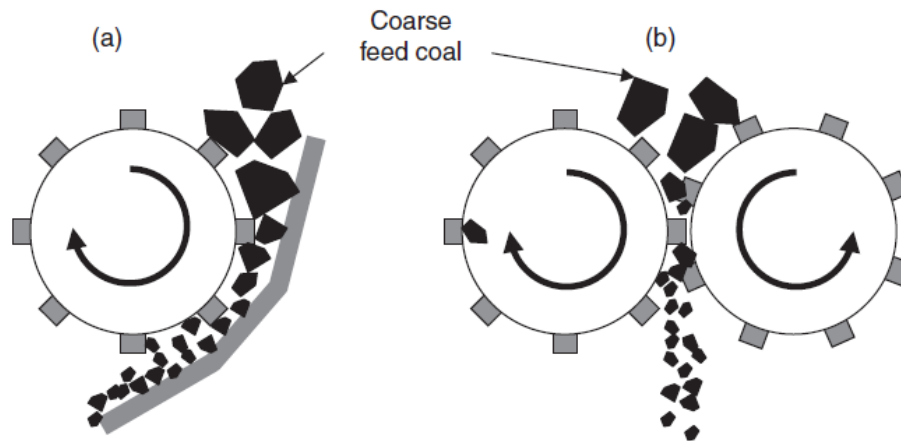


Figure 2.13: Single and double roll crushers (Eisele, 2013)

2.4.5. Factors affecting coal breakage

Coal is a weak banded material (Esterle, 2008) whose strength and resistance to fracture may be influenced by its geochemical and geomechanical properties. According to Esterle (2002), the coal's strength properties differ depending on the rank, composition, and texture. Particle breakage is dependent on the chemical and physical properties of ore. Physical properties include the shape, porosity and size of the ore while chemical properties include the presence of impurities, cleats, macerals etc. Additionally, another factor that affects coal breakage is the applied external force. Irrespective of the breakage mode, the introduction, and an increase in the applied stress increases the extent of the material damage and resulting its degradation (Esterle, 2002). In this section, the effect of some of the coal properties on breakage will be discussed.

2.4.5.1. Macerals

The coal's macerals content has an influence on the mechanical strength of coal (Falcon and Falcon, 1987). Inertinite is the hardest maceral group, followed by vitrinite and liptinite (Falcon and Falcon, 1987). However, according to some studies it was reported that inertinite contains more pores than vitrinite and liptinite (Mishra and Sing, 2017; Cardott *et al.*, 2018). Yu *et al.*, (2023) investigated the fracture and porosity evaluation of coal under uniaxial compression using an X-ray three-dimensional scanning microscopy. According to their findings, when

subjected to uniaxial loading, the distribution features of pores and fractures are closely linked to the internal stresses propagating. Conversely, when subjected to axial force loading, internal fractures persist, and micro-fractures are produced. (Yu *et al.*, 2023). Vitrinite rich coal are subject to conchoidal fracture due to their smooth texture (Schweinfurth, 2009). This implies that vitrinite rich coal undergoes breakage in a glass like manner. Salman and Gorham (1999) performed impact and compression tests on glass spheres. At low speeds, breakage was primarily due to a brittle and elastic behaviour whereas at high speeds or force, breakage is due to inelastic deformation under the impact site (Salman and Gorham, 1999).

2.4.5.2. Mineral matter

Coal strength is influenced by the distribution of mineral matter content in the coal matrix. (Falcon and Falcon, 1987). Mineral matter interlocked in coal may either be syngenetic or epigenetic minerals. Minerals amassed in cleats are somewhat easy to remove using crushing and washing processes while minerals that are present as either big species intergrown as coal macerals or as finely scattered mineral particles are challenging to separate and produce more middlings (Holuszko, 1994). Previous studies investigated the influence of mineral matter on coal properties. Cheng *et al.*, (2020). found that coal reservoirs with high mineral content and mineral infused fractures showed poor compressibility. Fu and Feng (2020) found that under uniaxial conditions, the existence of minerals improved the coal maximum strength, elastic modulus and residual strength. Figure 2.14 below shows different types of minerals in coal and possible effect on washability.

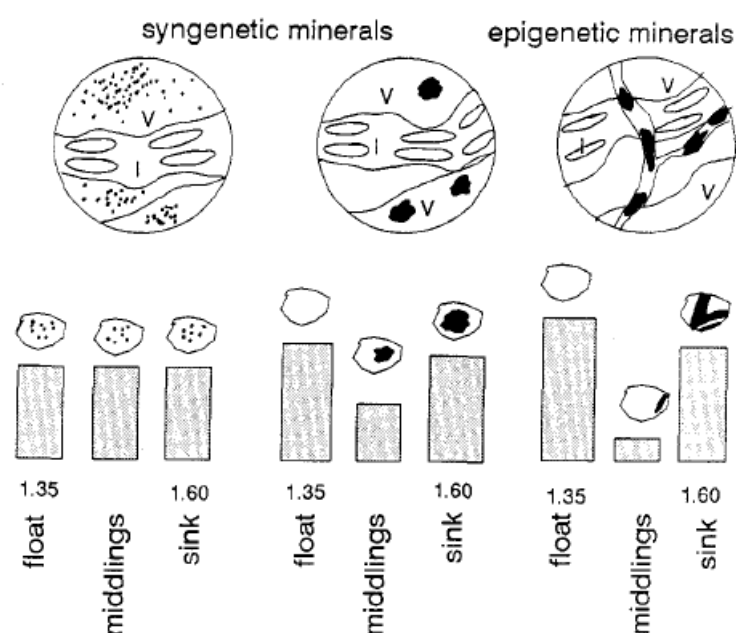


Figure 2.14: Type of mineral associated with coal and possible effect on washability (adapted from Holuszko, 1994).

2.4.5.3. Physical-mechanical properties

- **Hardness**

According to Honda and Sanada (1956), a material's hardness is basically a reflection of its plasticity and, to a lesser extent, its elastic properties. Coal's hardness is influenced by the composition of different macerals, lithotypes, mineral matter, carbon and moisture content (Falcon and Falcon, 1987; Speight, 2005:158). Inertinite has the greatest hardness, vitrinite hardness is moderate while liptinite has the lowest hardness (Falcon and Falcon, 1987). As the coal rank increases, its VM, moisture content, and hydrogen content (%) decrease and its structure tends to resemble graphite (Dasgupta, 2016). The increase in rank is associated with an increase in the carbon and energy contents and a reduction in the moisture content (Eskom, 2021).

Kozusnikova (2009), studied the microhardness and elastic modulus of coal component using the indentation (Vickers hardness) technique. High coalification coals reportedly had lower microhardness and elastic modulus values than lower coalification coal (Kozusnikova, 2009). The study by Hower *et al.*, (2008) found that the microhardness of pseudovitrinite was greater than telovitrinite. This indicates that the different macerals group have an influence on the hardness of the coal.

- **Friability**

Friability may be defined the measure of the coal's strength or ease of compressibility; the ability to resist size degradation on handling (Speight, 2020; Falcon and Falcon, 1987). The susceptibility of coal to breakage is dependent on the coal's toughness, elasticity, fracture properties and strength (Speight, 2020). Low rank coals, associated with high moisture are nonfriable and tend to resist size degradation (Lett and Ruppel, 2004; Speight, 2020). Low rank coals readily oxidize due to the increase amount of surface exposed to oxidation (Speight, 2020).

Friability generally increases with the coal rank, reaching the highest for low volatile bituminous coals and subsequently lowering for anthracite (Lett and Ruppel, 2004). The study by Bird (1951) show that high friability of semi-anthracite was attributed to its brittleness as compared to bituminous coal (Bird, 1951). In the study by Singh and Jha (2018), the friability of dull coal was reportedly high as compared to banded dull coal and banded coal.

- **Particle size and shape**

Particles tensile strength differs with particles size following the power law function (Xu and Wang, 2017). Coarse particles are associated with large amounts of impurities and micro-cracks leading to decreased particle strength (Vervoor and Scarlett, 1987; Tavares and King, 1998). Coarse particles contain large cracks and are more susceptible to breakage (Oberholzer and van de Walt, 2009). The compressive strength decreases with an increase in size (Falcon and Flacon, 1987). As the particle size decrease, the particles become more resistant to breakage (Shi, 2016). Particle shape influences the breakage energy by modifying the breakage characteristics of irregular particles (Gan *et al.*, 2019). Particles with sharp edges promotes the formation of large local forces (Vervoor and Scarlett. 1987).

2.5. Coal washability

Coal is composed of a variety of macerals and may contain different forms of gangue material which must be liberated to produce a clean coal, suitable for use in other industries applications. An essential component of a coal seam economic assessment is its washability. To determine the economic viability of coal seams parameters such as the geological mining conditions and the seam properties (amongst others the yield and coal quality) must be considered (Holuszko, 1994). The relationship between a coal's ash, mass, and density distributions determines its washability; this relationship is typically shown as washability curves (Hosseni, 1997). A well-defined washability curve provide researchers with valuable information pertaining to a coal seams' coal quality and associated mineral matter and may assist in identify the most suitable beneficiation processes and equipment.

Coal washability may be evaluated using a variety of methods, these includes traditional and destructive and new and emerging densimetric analysis techniques. Botlhoko (2023) employed the traditional zinc chloride float-sink and the RhoVol method (see 2.7) to determine the washability of coal samples from the Highveld, Witbank and Molteno-Indwe coalfields. Hosseni (1997) used image analyses methods to determine the washability of fine coal. Nguyen *et al.*, (2023) used computed X-ray tomography to analyse coal washability. These techniques assisted researchers to generate washability curves for various size particle top sizes and establish the relationship between the coal's ash and density.

The coal's inherent properties should be considered when designing processing plants for coal washing. Understanding these washability traits is essential to designing effective and profitable beneficiation facilities and guaranteeing the profitability of mining activities.

2.6. RhoVol densimetric analyser

The RhoVol is a densimetric apparatus that weights and takes measurements of individual ore samples using a series of cameras placed at different angles for volume determination and a rapid mass weighing compartment to determine particle density (Fofana and Steyn, 2017). The cameras capture and produces real-time 3-D reconstructed images of individual particles volume and more information such as particle size and shape morphology can be obtained (Fofana and Steyn, 2017, Steyn and Cronje, 2017). The RhoVol reportedly has a weight error margin of 0.5% (High, 2018). The RhoVol is also equipped with a sorting module that can sort ore particles into specified fractions of any one of the available parameters of the ore as pre-determined by the user. Figure 2.15 below shows the RhoVol densimetric analyser at NWU on loan from De Beers Group Ignite.

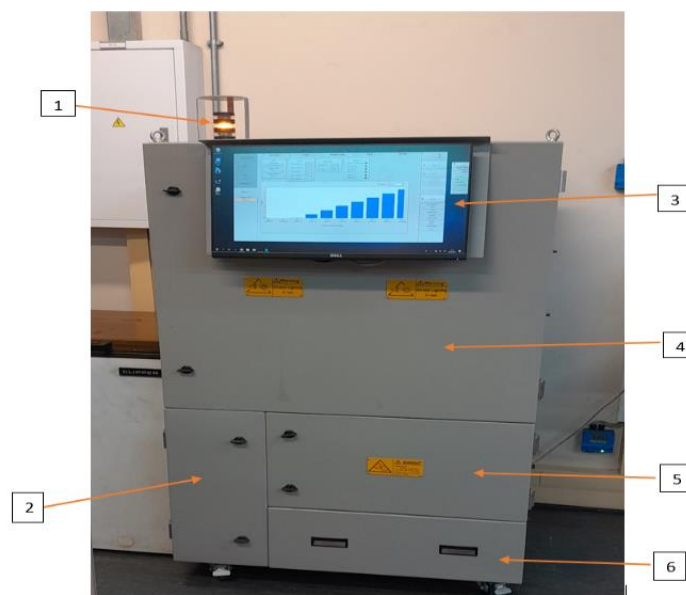


Figure 2.15: The RhoVol densimetric analyser at NWU on loan from De Beers Group Ignite

- 1 – Operating light/ (colours green, orange and red indicating the state of the machine)
- 2 - PC access door (gives access to the control PC)
- 3 – Touch screen (GUI, machine is controlled, and operating parameters are set)
- 4 – Front door (front door of the machine whereby the primary and secondary feeders, weighing scale and VSFD can be accessed)
- 5 – Sorting tray (whereby particles are collected and sorted into their respective sorting bins)
- 6 – Sorting bins drawer (contains 15 sorting bins).

The ore is initially introduced at the top of the RhoVol into feeders and the movement each particle is controlled by laser sensors that enables individual densimetric analysis of one particle at a time (Fofana and Steyn, 2019, Steyn and Cronje, 2017). After densimetric analysis, the ore sample is collected in bins at the bottom of the machine. The ore sample are separated into different bin compartment based on the user's machine configurations and set parameters (Fofana and Steyn, 2019, Steyn and Cronje, 2017).

The RhoVol is fast densimetric analyser with the ability to process on average 1000 particles/hr. The RhoVol can process particles with a mass range of between 6-mg – 150g. The inlet hopper has a maximum particle intake capacity of 2L. Samples to the RhoVol, however, should be free of moisture and dust and must be screened accordingly to the required particle size fraction (Fofana and Steyn, 2019). The RhoVol can process coarse particles of sizes between 8 to 25 mm and fine particles ranging from 3 to 8 mm (Fofana and Steyn, 2019, Steyn and Cronje, 2017). The RhoVol however, tend to overestimate the particle volume due to its inability to identify hidden cavities and porosity in samples such as coal (Mangera *et al.*, 2019). Therefore, a correction factor error margin must be determined by comparing the RhoVol calculated density average against true density data from pycnometric analysis.

The RhoVol employs non-destructive analytic techniques making it possible to reuse the sample. The RhoVol can be used to determine the washability of coal in a non-toxic and non-destructive manner unlike traditional float-and-sink methods that used hazardous chemicals and time consuming (Botlhoko, 2023; High, 2018). Botlhoko (2023) investigated the washability of four different coals using the traditional zinc chloride float-sink technique and compared it to the RhoVol densimetric analyser results, and it was shown that the washability determined by the RhoVol compared well with the results of traditional float-and-sink analysis. The RhoVol can thus be utilized for densimetric analysis without the need for float-and-sink analysis (Botlhoko, 2023)

CHAPTER 3

MATERIALS AND METHODS

In this chapter, the materials, equipment and experimental procedures used in this study are explained. The materials used and equipment are detailed in sections 3.1 and 3.2 respectively. Section 3.3 describes in detail the methods used for sample preparation and analysis which include impact and compressive breakage, RhoVol densimetric, pycnometric, proximate and particle size distribution analysis. Despite the possibility of breakage of some of the coal during mining and transportation, precautions were taken to minimize the formation fines and particle breakage during sample handling and in between the experimental processes. Precautions were also taken to keep the sample mass loss to a minimum during the experimental procedure.

3.1 Materials

3.1.1 Waterberg coal

ROM coal samples from the Grooteegeluk formation in the Waterberg coalfield was obtained and used for this study. Coal from the Waterberg coalfield was selected because it provides between 40 and 50 percent of South Africa's remaining coal resources (Moumakwa, 2009, Hancox and Götz, 2014) and is seen as potential replacement for the depleting Witbank, Highveld and Ermelo coalfields coal reserves (Jeffrey, 2005). The coal is predominately laminated interbedded coal with mudstones (Hancox et al, 2014) with a layered coal structure of bright vitrinite and inertinite rich mineral matter (SACPS,2015, Wagner *et al*, 2019).

In this study, lumps coal from the Waterberg coalfield will be broken down to different top sizes using compressive and impact breakage modes. Horsfall (1980) categorizes coarse coal as coal with lower size limit of around 6 mm while small coal as that with an upper limit of 15 mm to lower of 0.5 mm wedge-wire mesh. Fines (<1 mm) are the underflow of a 0.5 mm wedge-wire screen and can be treated using flotation devices (Horsfall, 1980). Depending on their applications, the domestic market require different sized products of any specific coal grade i.e. 0 mm x 6 mm for duff, 6 mm – 25 mm for peas and 25 x 40 mm for small nuts (Steyn and Minnit, 2010).

3.2 Equipment

A detailed description of the apparatus and equipment used in this study and their purpose is given. Pictures of some of this equipment can be found in section 3.3.

Table 3.1: Apparatus and equipment used

Equipment	Description	Purpose
Jaw crusher	Jaw crusher	Mechanical device used to reduce large ROM fragments into small particles.
Sieves	Labotec ® stainless steel sieves	Used to separate crushed coal into different size fractions.
Rudimentary lawn roller	80 kg lawn mower (see Figure 3.3)	Used for compressive breakage of the coal samples.
Drop weight impact rig	See figure 3.2	Impact breakage of the coal samples.
RhoVol densimetric analyser	Debtech RhoVol coarse particle densimetric analyser (-25 mm to +8 mm), and the MK1 Rhovol densimetric analyser at NWU (-8 mm to +3 mm).	Densimetric analyser used to estimate particles' density by measuring their mass and estimating their volume using a series of cameras and image processing software.
Gas Pycnometer	Micrometrics ® AccuPyc II 1340	A laboratory device that uses Archimedes' displacement principle to determine a particle or substance's actual density

Equipment	Description	Purpose
Steel frames	Rectangular steel plates with a width of 0.5 m and length of 2 m with flat bars of varying sizes (12, 8, 6, 4 and 3 mm) on the sides. See Figure 3.3	Used to contain coal particles undergoing compressive breakage at different size intervals and to minimise the formation of fines.
Spacers	Steel rings of 10 mm diameter varying thickness (12, 8, 6, 4 and 3 mm).	Used to stop the dead weight at different size intervals.
Electronic scale	Sartorius® AG GÖTTINGEN. Model number: PMA7500	Used to weigh coal samples
Rotary splitter	SMC rotary splitter	Used to split and divide the coal into sub-samples
Paint brush	50 mm paint brush	Used to sieve out coal samples.
Shovel	Steel shovel	Used for cone and quartering.
Plastic bags	Airtight plastic bags	To contain separated coal particles.

3.3. Experimental procedure

The effect of impact and compressive breakage modes on the coal yield was investigated using the RhoVol densimetric analyser. Large ROM coal sample particles were initially crushed using a jaw crusher to reduce the coal to a top particle size of 16 mm. Particles were then subjected to impact and compressive crushing to different top sizes (12 mm; 8 mm; 6 mm; 4 mm and 3 mm) followed by RhoVol densimetric and pycnometric analysis.

Figure 6.1 in Annexure A shows the detailed experimental procedure used in this study.

3.3.1. Sample preparation

A laboratory jaw crusher was used to crush the bulk coal to top size 16 mm. Top size control sieves were used to screen the crushed product and oversized particles were recrushed until all particles were smaller than 16 mm. The bulk coal sample of approximately 8 kg was then repeatedly subjected to the cone and quartering technique (SANS 18283:2007/ISO 18283:2006), as seen in figure 3.1. until the desired mass of 2 kg was achieved. The process involves thoroughly mixing the sample using a shovel to form a conical heap as shown and then flatten the top followed by dividing the sample into equal quarters of approximately the same mass. Thereafter, opposite quarters—that is, 1 and 3 or 2 and 4 are then combined once more to form conical heaps. The mass of sample was reduced by multiple steps of coning and quartering, discarding opposite quarters at each step until the two opposite quarters combined each weighed about 2kg. The two samples were then combined, and cone and quartering were done to divide the sample into two 1 kg samples. One 1 kg sample was used for compressive crushing experimental work while the other 1 kg sample was used for impact breakage test work.



Figure 3.1: Cone and quartering sampling method

3.3.2. Breakage modes

The next sections describe how the sample was broken at each stage and how the top size at which it was broken was controlled.

3.3.2.1. Impact breakage

Using a custom-built drop weight impact rig, the 1 kg coal sample was subjected to impact breakage in compliance with SANS 401:2010 for the "Standard test method of drop shatter test for coal." as seen in Figure 3.2. The drop weight rig was fixed with a steel plate weighing 14.65 kg secured at a height of 0.9 m using a safety pin. The bottom of the drop weight rig was encased with steel plates on three sides and a removable high strength PVC plate to contain the coal sample and ensure minimal particle loss during impact testing. A single layer of the coal sample was placed at the bottom of the impact rig with steel rings spacers of either 12 mm; 8 mm; 6 mm; 4 mm or 3 mm depending on the top size of that particular run.

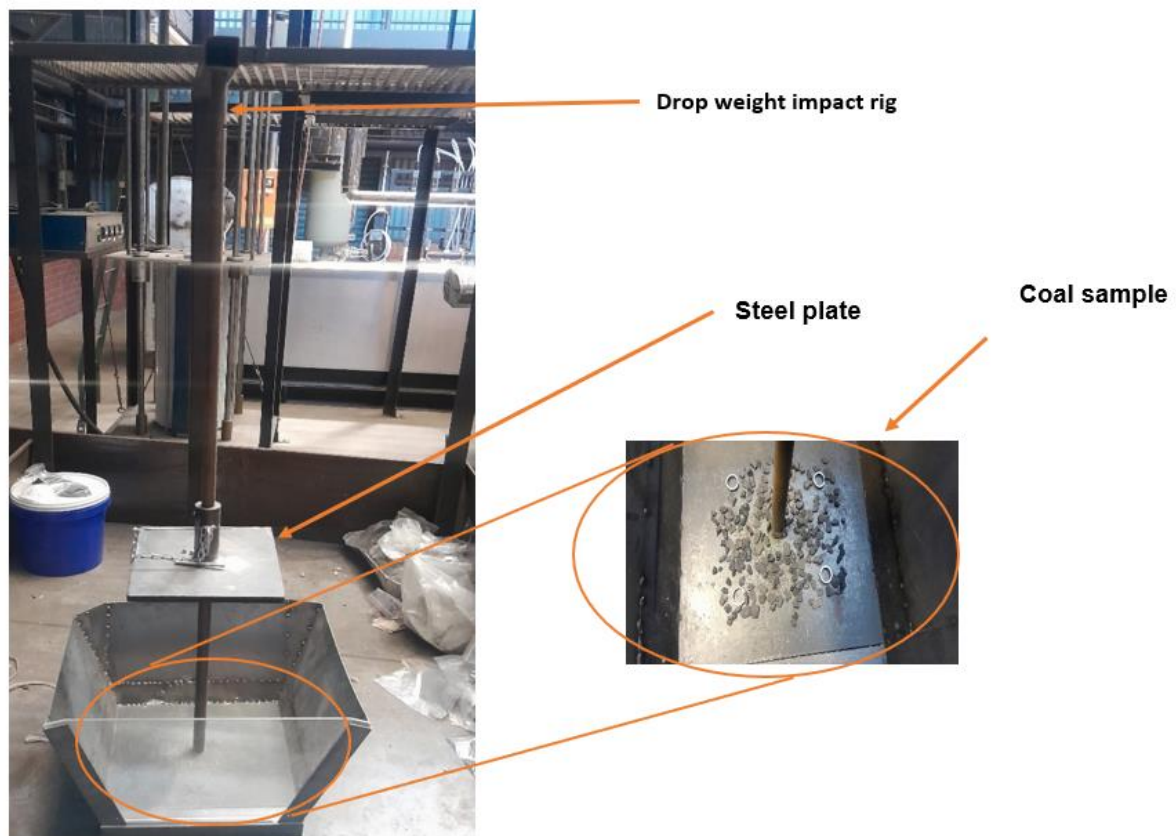


Figure 3.2: Drop weight impact rig for impact breakage

The coal was placed randomly in a single layer at the bottom of the impact rig to avoid inter-particle breakage whereas the spacers ensured that the desired top size is achieved and to minimize the production of fines. The initial step involves crushing the 16 mm sample by placing 12 mm spacers at the bottom of the impact rig for top size control. The safety pin was then removed, and the steel plate was released from a height of 0.9 m to enable optimal particle breakage. To ensure that the particles get an even impact force, a steel pipe was installed in the centre of the drop weight rig to guide the movement of the steel plate. After crushing, the removable plastic plate was removed, and the coal sample was screened to their top size using 12 mm top size control sieves. Oversized particles were then further subjected to impact breakage and screened again until every particle had gone through the top size control sieves. After densimetric analyses, the particles were combined, and process was repeated by progressively reducing their top sizes to either 8 mm, 6 mm, 4 mm and 3 mm via impact breakage.

3.3.2.2. Compressive breakage

Compressive breakage of the other 1 kg coal sample was also done progressively using a 80 kg lawn roller and a rectangular steel frame of lengths of 2 m and widths 0.5 m and varying heights of either 12 mm, 8 mm, 6 mm, 4 mm or 3 mm depending on the required top size of that experimental run. These top sizes were selected to minimize the quantity of fines generated and in accordance with the sizes needed for industrial applications. To avoid inter-particle breakage, the coal particles were randomly place in a single layer within the steel frame and the particles were subjected to compressive stress by pulling a lawn roller over the steel frame. The lawn roller ensured that a constant compressive stress was applied to the particles resulting in compressive breakage. Once more, the samples were screened to their top size using sieves of either 12 mm, 8 mm, 6 mm, 4 mm or 3 mm aperture sizes (ISO, 1994; SANS, 1994) depending on the experimental run. Again, oversized particles were then subjected to compressive crushing and the process was repeated until all particles passed through the sieves. Figure 3.3 shows the compressive breakage test set-up.

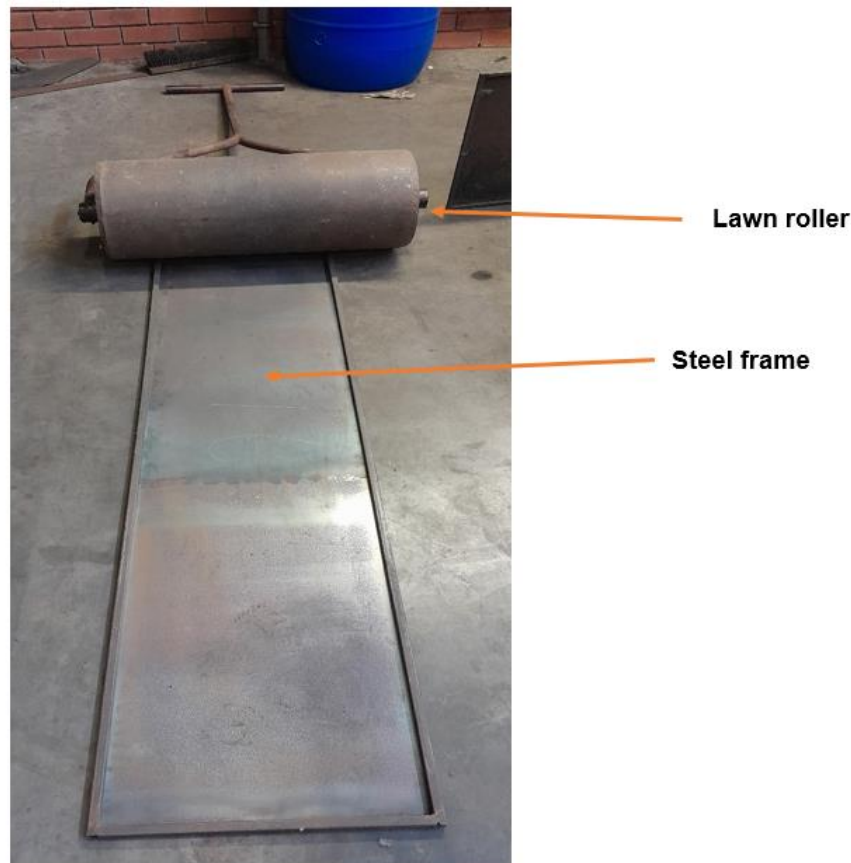


Figure 3.3: Lawn roller and steel frame for compressive breakage

3.3.2.3. Rotary splitter

A rotary splitter was used to divide the different top size crushed coal samples to obtain a smaller quantity of test material in accordance with the manual sampling standard ISO 18283:2006. Due to time constraints and the RhoVol machine availability, densimetric analysis were done on the divided crushed sub-samples to generate coal washability curves. This technique is frequently used in laboratories and sectors such as mining and metallurgy where representative samples are essential (Minnit *et al.*, 2024). The study by Potgieter (2017) used rotary splitter sub-samples to generate Mozambique Moatize coalfield washability curves. The crushed coal sample was deposited into the conical bucket at the top. Due to the rotary machine vibration, the sample was allowed to move down the chute and into 6 sub-sample buckets. The rotary action and the design of the splitter ensure that each container receives a representative portion of the original sample.

3.4. Fines production

During each breakage stage, precaution was taken to minimise the generation of excessive fines. However, the proportion of fines generated varies substantially based on the type of comminution process, as a result, fines were deemed outside of the scope of this investigation.

The RhoVol densimetric analysers used in this investigation can only analyse particles between -25 mm to +3mm size ranges. Particles less than 3 mm (-3 mm) were considered as fines and were removed from the samples using screening sieves after each subsequent crushing stage. In practice, fines are normally removed before dense medium separation (DMS) processes due to handling and processing difficulties. As a result, the proportion of fines generated in this study was not considered and fines measurements were not included the washability calculations. The yield curves presented in chapter 4 are optimistic and overestimated as they do not consider they proportion of the discarded fines.

The RhoVol densimetric machine at NWU is calibrated to process particles between -8 mm and +3 mm. When introduced into the RhoVol machine, fines (-3 mm) are problematic and may get lost or lodged between the machine components such as the sorting funnel tube causing wear and tear. The dust associated with the fines may also interfere with the volume measurement system and would often accumulate on the machine light curtains.

3.5. Analytic methods

The RhoVol densimetric machine was used to perform densimetric analyses on the crushed coal samples and pycnometer analyses was done to produce a volume correction calibration. Proximate and ultimate analysis measurements were done to determine the ash, moisture, volatile matter and fixed carbon contents of the coal. These analytical methods are discussed further in detail in the following sections.

3.5.1. RhoVol densimetric analysis

- **RhoVol principle of operation**

Figure 3.4 shows the internal components and particle processing stages of the RhoVol densimetric analyser. Each component is numbered and labelled as indicated in figure 3.4 and their functions are explained. The particle processing and analysing stages are explained below.

1. An entrance hopper located at the top of the RhoVol receives ore particles, which are then deposited into the primary feeder tray (1).
2. The ore particles are transferred from the primary feeder tray to its open end, where they are fed into the secondary feeder (2). The particle feed rate onto the secondary feeder is controlled by a laser distance.
3. The secondary feeder tray carries the ore particles, which are then dropped into the scale gate (3).
4. The scale gate lets the particle onto the scale (4), where the mass is recorded.

5. After the mass is recorded, the chute gate opens, and the particles can fall through the light curtain (5) into the claw (6).
6. The claw opens and lets the particle fall through the secondary light curtain to the VSFD (7). The VSFD (7) uses a number of cameras to measure the volume of the particle.
7. After the mass and volume of the particle are measured, the density is calculated.
8. The measured particle falls into the claw (9) and is then released into the sorting funnel (10).
9. The particle is then collected in the bin (12) at the bottom of the machine. The mass and volume measurement process is then continued for the next particles until the completion of the sample batch. Based on the set machine parameters¹, each particle is sorted according to their density. (extracted and adapted from Debtech operator's manual, E10-100000-750 rev 1.0; Steyn and Cronje, 2017; Fofana and Steyn, 2019).

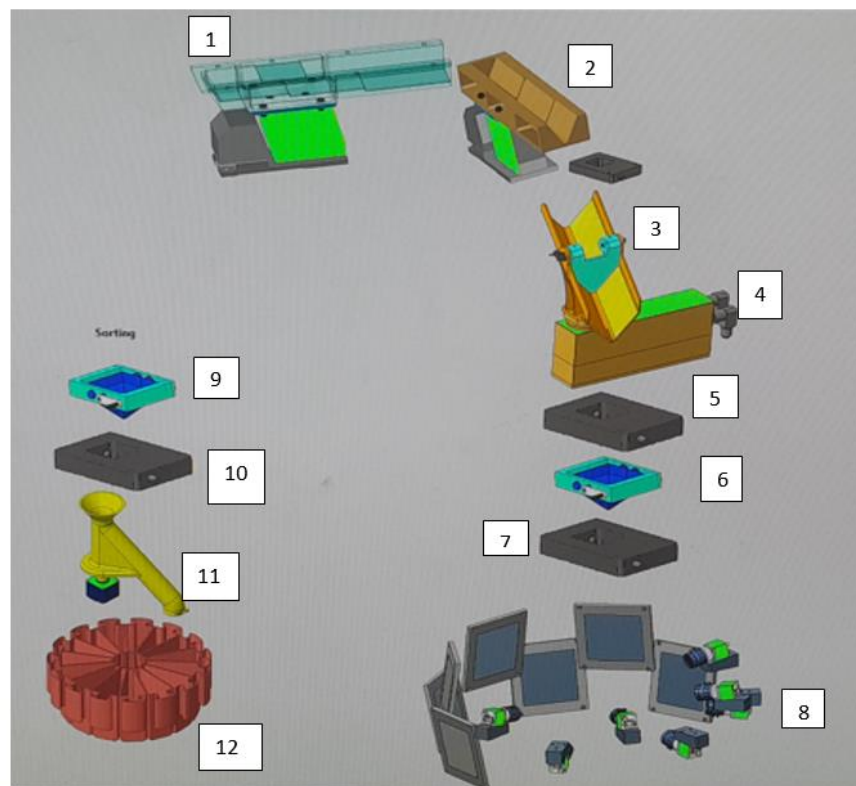


Figure 3.4: RhoVol operating principle

➤ 1- Primary feeder

¹ Particles were sorting into 10 density classes between 0.5-4. Particles outside of these limits were collected either in the underflow and overflow bins.

- 2- Secondary feeder
- 3- Scale gate
- 4- Weighing station
- 5- Light curtain
- 6- Claw
- 7- Secondary light curtain
- 8- VSFD system
- 9- Claw
- 10- Light curtain
- 11- Sorting funnel
- 12- Sorting bins

The density of each individual particle is measured and estimated using the RhoVol densimetric analyser and particles are separated according to their densities. Two RhoVol machines were used for the purpose of this study. Both machines operate and analyse particles the same way but have different limitations. Coarse particles (16 to +8 mm) were analysed using the coarse particle RhoVol densimetric analyser at De Beers Group Ignite (Debtech) site. This RhoVol model can process and analyse particles up to 25 mm in size but is unable to analyse smaller particles (-8 mm) without the machine giving you persistent errors and alarm warnings. This RhoVol is not equipped with a sorting function, and thus is not able to sort coarse particles based on their density, elongation, particle size, volume, compactness etc. The RhoVol at NWU (on loan from Debtech) on the other hand is equipped with a sorting function and can analyse particles of top sizes between -8 mm to + 3 mm. NWU RhoVol limitations is that it cannot analyse coarse (-25 mm to +8 mm) and fine (-3 mm) particles.

After each crushing stage by either impact or compressive breakage the screened particles (top size(s) 12 mm, 8 mm, 6 mm, 4 mm or 3 mm, ISO, 1994; SANS, 1994) were analysed using the RhoVol. Coal particles of top sizes 16 (head sample), 12 mm and 8 mm obtained after impact and compressive breakage were analysed using Debtech RhoVol. Particles of top sizes 6 mm, 4 mm and 3 mm were analysed using the RhoVol at the NWU, which is equipped with a sorting function; separating the coal particles based on their densities and collected in bin located at the bottom of the machine. The density is calculated by individually measuring the mass of each particle and estimating their volume using a series of cameras which reconstruct and produce 3D images of each particle (De Beers Group, 2013). The data of each analysed particle is shown in real-time and arranged in a typical spreadsheet fashion, with details for every particle.

The RhoVol tend to overestimate the particles' volume due to its inability to identify hidden cavities and porosity in samples such as coal (Mangera *et al.*, 2019) therefore a correction factor is required. After analysing and sorting particles according to density, the particles are then stored in separate bags to be analysed further. Gas pycnometric analysis which will be further discussed in section 3.5.2 is then conducted on the sorted particles collected from each bin for volume correction calibration.

3.5.2. Pycnometer analysis

Helium gas pycnometer was used to determine the true density of the sorted coal particles from the RhoVol bins. Densimetric analysis using the pycnometer were conducted in accordance with, and as describe by ISO standard 12154:2014(E) (ISO, 2014). Coal samples sorted according to their density from the RhoVol densimeter bins were weighed and their mass was recorded. The density of the coal particles in the RhoVol bins ranged from 0.5 to 4² and the particles were sorted into 10 density categories. Coal particle outside of these density limits were recovered either in the underflow/overflow bins. The weighed sample was then deposited into a sample cell and then placed into the pycnometer. The recorded mass of the sample was then entered into the pycnometer and the pycnometer performed density replicate measurement cycles automatically.

Upon completion of the cycles, density estimates determined by the pycnometer were recorded. The pycnometer measurements obtained were then used to calibrate the RhoVol data. The coarse particles RhoVol machine was not equipped with particle sorting capabilities and as such, pycnometer analyses could not be done on top size 16 mm, 12 mm and 8 mm samples. Pycnometer analysis was done on the sorted 6 mm, 4 mm and 3 mm coal samples and used to calibrate the RhoVol data. Micromeritics ® AccuPyc II 1340 helium gas pycnometer used in this study is shown below in Figure 3.4



² set limits on the density range for automatic determination of class boundaries

Figure 3.4: Helium pycnometer (Kromtek, 2013)

3.5.3. Proximate and ultimate analyses

Proximate and ultimate coal analysis were performed in accordance with the standards mentioned in Table 3.2. Proximate and ultimate analysis measurements were done to determine the quality of the coal before crushing.

Table 3.2: Proximate and ultimate analysis standards and procedures

Analysis	Procedure
Sample Preparation	SANS 18283:2007 / ISO 18283:2006
Proximate analysis (Moisture content wt.%)	SANS 5925:2007
Proximate analysis (Ash content wt.%)	SABS ISO 1171:1997
Proximate analysis (Volatile matter content wt.%)	SABS ISO 562:1998
Proximate analysis (Fixed carbon content wt.%)	By difference
Gross calorific value (MJ/kg)	SABS ISO 1928:1995

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, data obtained from the experimental procedure is analysed and interpreted. This is done in order to address the set-out research scope and objectives as mentioned in the introduction under chapter 1. The data obtained from the RhoVol and the gas pycnometer are analysed and interpreted to determine the correction factor and investigate the effect of breakage mode and top particle size on coal liberation. The effect of breakage mode and top size on particle shape will also be investigated. Graphical representation(s) of washability curves, densimetric curves and discussions around the coal proximate analysis will also be given. Due to the RhoVol densimetric machine limitations, - 3 mm were not considered in this study. Therefore, the yield/washability curves used to analyse the degree of liberation are essentially idealistic since they do not account to the fact that certain amounts of coal are lost to the fines. Appendix B contains supplementary data and other graphs generated not included in this chapter.

4.1. Proximate analysis

Coal from the Waterberg coalfields (Grooteegeluk formation) contain high ash content of between 50-60% and around 30-35% volatile matter (Jeffrey, 2005b; Hancox and Götz, 2014; Wagner *et al.*, 2019). The high ash content necessitates beneficiation to improve the coal grade (Dreyer, 2011; Hancox and Götz, 2014; Wagner *et al.*, 2019) using different coal liberation techniques. In this section, the proximate analysis data of the coal will be discussed. Table 4.1 shows the proximate analysis data of the Waterberg head sample. The high ash content above 60% in the head sample shown in the proximate analysis report is consistent with that reported in the literature (Jeffrey, 2005a) indicating that coal from the Waterberg coalfields is of poor quality and that beneficiation of the coal is necessary to improve the coal grade.

Table 4.1: Proximate analysis of Waterberg coal sample used.

Sample	Top size	Ash content (wt%)	Moisture content (wt%)	Volatile matter (wt%)	Fixed carbon (wt%)
Head sample	16 mm	60,69	0,5	18,18	20,62

The ash content is not equal to the mineral matter, but it makes up the majority of the mineral matter in the coal after volatile substances like carbon and sulphur dioxide and water have been removed (Thomas, 2013). To further investigate the relationship between the ash content and particle size, proximate analysis was done on the coal particles at different sizes. Proximate analysis data was also done on two distinct sizes, 3 mm and 4 mm coal particles. Detailed discussions on the ash content at different relative density intervals is given in the following section. Supplementary data on the volatile matter, moisture and fixed carbon at different RD intervals can be found in the supporting appendix B.

Ash content

Figure 4.1 shows the average ash content of 3 mm and 4 mm top size coal particles at different RD intervals. It was observed that the ash content increased with the increase in the relative density (RD). It was observed that coal with a relative density of between 1.2-1.4 (clean coal) had the least ash content of < 20% whereas coal particles with high RD (> 1.9) was comprised of high ash composition (> 40%). Particles at low RD (< 1.4) are mainly composed of pure coal macerals and low mineral matter. High RD coal particles (> 1.9) are mostly composed of high mineral matter and small amount of coal macerals. Coal with the RD of between 1.4-1.8 represents the middlings, composed mainly of mineral matter and coal macerals. The middlings have an ash content ranging from 24-39%. It was observed that as the middlings RD interval increases, the ash content also increases. The increase in the RD means there is an increase in the amount of mineral matter contained, thus increasing the quantity of incombustible matter in the coal resulting in higher ash yields.

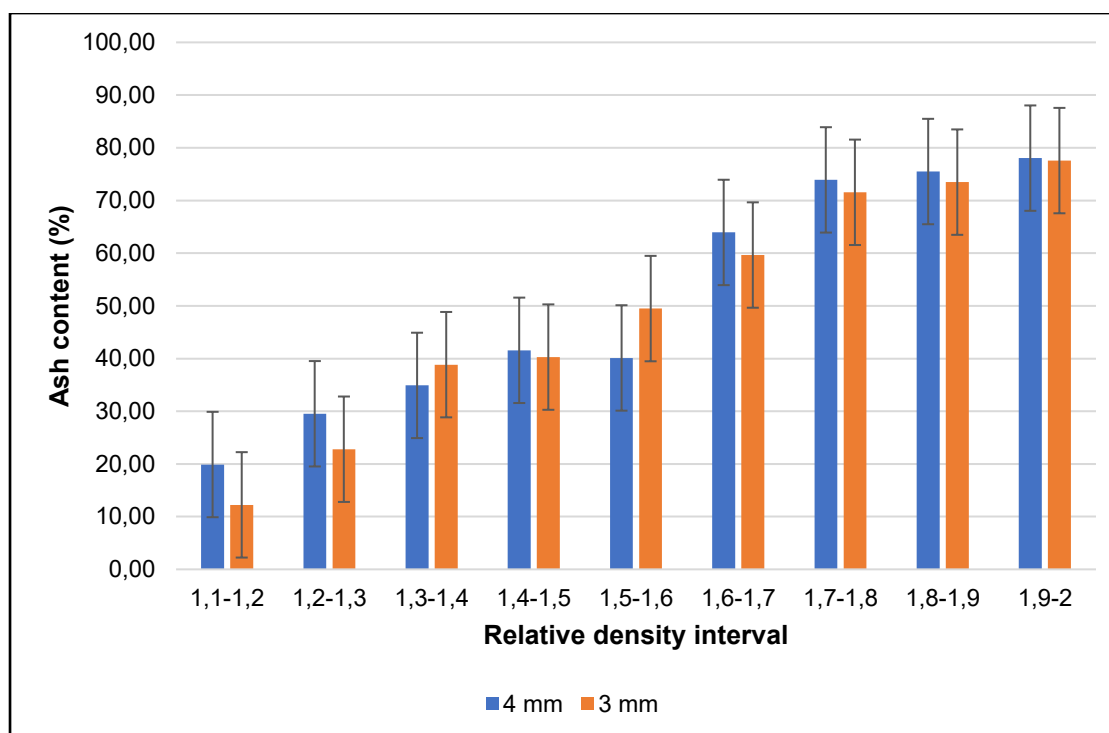


Figure 4.1: Ash content (dry basis) of particles in each bin and their relative density intervals

The size of the particles also had an influence on the ash content at different RD intervals. From Figure 4.1 it was observed that smaller particles (3 mm) with RD of between 1.2-1.4 contained the least amount of ash (12.2%) when compared to bigger particles (4 mm) with 19.9% ash. This may imply that crushing to a finer particle size liberated more coal macerals when compared to larger particles, although the error bars overlapped for both particle sizes at the same RD interval. The latter was also observed with coal middlings of RD between 1.4-1.6 even though the errors bars also overlap. There is an insignificant difference in the ash contents of the smaller and larger coal particles at RD >2.5.

Coal from the Waterberg coalfield is predominantly used as thermal coal for Matimba and Medupi power stations. According to Eberhard (2015) and Jeffrey (2005a), the characteristics and market requirements for ROM and washed South African coal should contain between 20-40% (ROM) and around 20-30% (thermal coal) ash content. Makgatho and Chirwa (2017) studied the characteristics of coal of thermal coal used by power stations in the Waterberg area. Proximate analysis show that coal samples contained ash content ranging from 29-35% with a sulphur (S) content of 1.15-1.49 wt% (Makgatho and Chirwa, 2017). The ash content reported in figure 4.1 is consistent with that used in local power stations for power generation. The high ash and S content in coal have an influence on the design of major power generation equipment found in power station and ash handling systems (Santhosh Raaj *et al.*, 2016).

4.2. Determining the correction factor

Bothloko (2023) gives an in-depth discussion and procedure on the determination of the correction factor using the RhoVol and pycnometer data. This is done by calibrating the RhoVol data with pycnometer data and determining the density correction factor. The density correction factor is applied onto the RhoVol data because the 3D image densimetric analysis technique is unable to accurately determine the true volume of porous ore samples. The method is unable to capture hidden cavities and may overestimate the particles volume (Bothloko, 2023). Not factoring the correction factor may negatively affect the credibility of the washability results obtained (Bothloko, 2023).

It is worth noting that the RhoVol densimetric analyser at De Beers for the coarse particles, (between 16 mm and 8 mm) is not equipped with a particle sorting capability. As such, density separation of 16 mm and 8 mm particles could not be done using the coarse RhoVol densimetric analyser. As a result, volume calibration was done using the sorted 6 mm, 4 mm and 3 mm crushed coal samples. The RhoVol NWU densimetric analyser automatically determined the density intervals of each bin and separated the particles into different density classes. The average RhoVol density in each bin is compiled as the sum of the particles over the sum of the apparent volumes and is shown in the following equation.

$$\rho_{\text{RhoVol}} = \frac{M}{V} \quad [2]$$

To determine the density correction factor, the true vs raw RhoVol density relationship was determined using the calculated average densities of the separated particles in each bin and subjecting them to helium pycnometry to establish their true density. Figure 4.2 shows the correlation between the average RhoVol density (bulk) and pycnometer density plot. Since the coarse particle densimetric analyser machine at De Beers does not have sorting capabilities and could not separate particles based on their RD densities, it was assumed that the coal properties were independent of the particle sizes, and a constant/static density correction factor was determined using RhoVol and true density data obtained of the smaller particles (6 mm, 4 mm and 3 mm). The combined average RhoVol and pycnometer density data of compressive and impact crushed 6 mm, 4 mm and 3 mm was used to determine the static correction factor. The static correction factor ratio is the average of all bins in a sample (Bothloko, 2023).

The calibration of the raw RhoVol densimetric data is necessary since the 3D image densimetric analysis technique cannot precisely determine the true volume of porous ores such as coal. This may result in the overestimation of the particles volume necessitating the

need for data calibration. The correction factor between the RhoVol and true densities was determined by applying linear regressions. This was done by fitting a linear correction factor using the average RhoVol bulk density and the pycnometer data of compressive and impact crushed coal particles and calculating the correction factor. The correction factor was determined as shown in equation 3 and the obtained linear function was applied to the RhoVol generated data (ρ RhoVol) for post-calibration.

$$\rho_{\text{corrected}} = 1.4331 \times \rho_{\text{RhoVol}} - 0.1154 \quad [3]$$

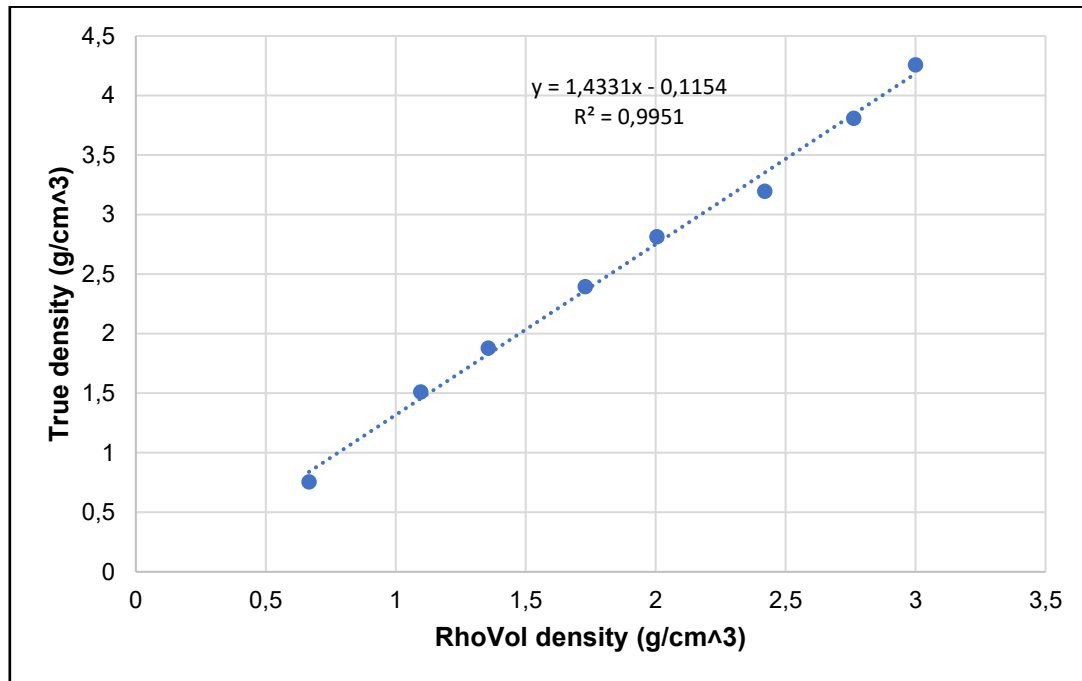


Figure 4.2: Correlation between the average bulk densities of the RhoVol and true densities of compressive and impact breakage coal particles.

A positive correlation coefficient of $R^2 > 0,99$ was obtained after applying linear regressions on the average RhoVol and pycnometer densimetric data. “The large and positive correlation coefficients ($R^2 > 0.97$) indicate that there is nearly a linear density difference between the RhoVol and pycnometer densities” (Bothloko, 2023). The slope and the intercept values were also determined for each breakage mode. The determined correction factor obtained was applied to the RhoVol derived densities (ρ RhoVol) in each bin to calibrate the raw RhoVol data. Figure 4.3 shows the uncorrected and corrected RhoVol vs pycnometer density distribution in each bin of 4 mm compressive crushed coal sample. Before the correction factor was applied, there are major discrepancies between the RhoVol and pycnometer data in each bin. Density measurements obtained using the RhoVol densimetric analyser are underestimated and do not correspond to those acquired using the pycnometer. After the application of the calculated correction factor, the RhoVol density measurements in each bin were corrected. The RhoVol

and pycnometer histograms after the application of the correction factor are almost identical, validating the correction success.

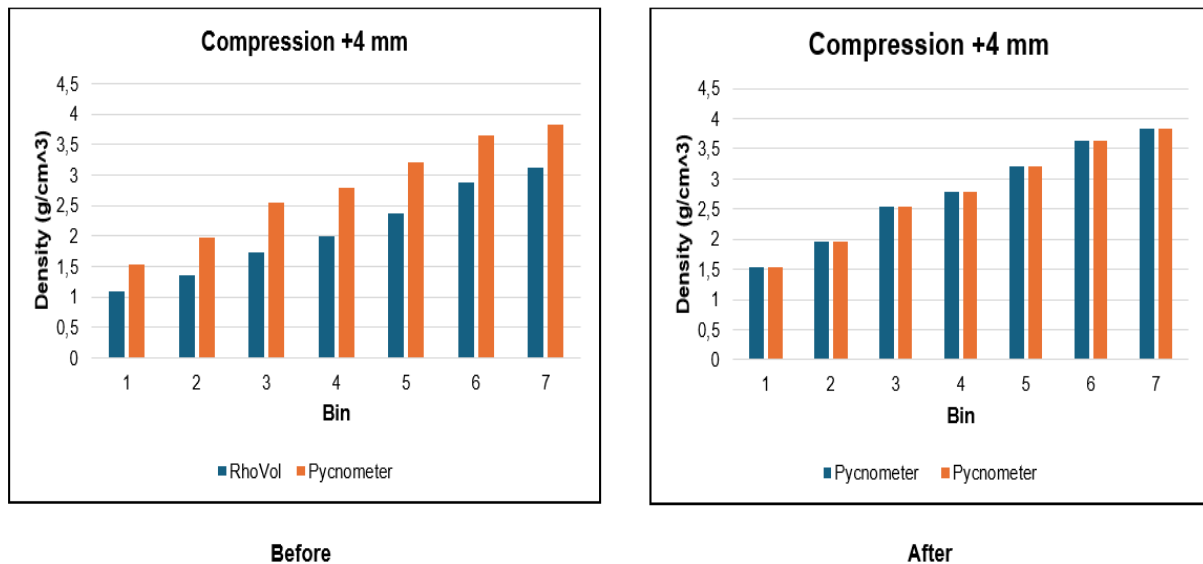


Figure 4.3: Uncorrected and corrected RhoVol densities in each bin vs pycnometer density distribution of the 4 mm compressive breakage sample.

4.3. Effect of breakage mode and top size on coal liberation

The Waterberg coal sample was subjected to compressive and impact breakage at different top particle sizes as discussed in the previous chapter (chapter 3). RhoVol densimetric analysis was done to determine the effect of these breakage modes on coal liberation. The particle top sizes chosen in this study were based on the required size for industrial applications. Compressive and impact breakage was performed to top sizes 12 mm, 8 mm, 6 mm, 4 mm and 3 mm while limiting the generation of fines. Due to the RhoVol machine limitations, the fines generated were not considered in this study. The nature of the fines produced varies greatly on the type of comminution process used and it was determined to be beyond the scope of this study. As a result, the washability/yield curves presented in this chapter are overestimated as they do not take into account the fines measurements. In this section, the results of the tests undertaken are presented in detail.

4.3.1. Compressive breakage

Figure 4.4 shows the results of the compressive breakage tests. It shows the density distribution of each sample after it has been broken down to a specific top size, i.e. one distribution for each top size from 16 mm to 3 mm. For ease of readability only the mass-by-density distribution of particles with a top size of 16 mm, 12 mm, 8 mm, 6 mm, 4 mm and 3 mm is represented in the diagram.

As shown in

Figure 4.4, a large amount of high-density (near dense) particles can be observed in the 16 mm head sample. The majority of the particles (about 70% by mass) have high densities of > 1.8 indicating that coal particles are predominantly composed of dense gangue matter (shale and rock). At high RD, the coal is associated with very high mineral matter content and low coal maceral content. About 30% (by mass) of the particles RD ranged from 1.6 – 1.8. Little to no particles can be seen in lower densities of < 1.5 . Coal from the Waterberg coalfields is heavily interlayered and is made up of distinct mineral structures, such as layers of mudstone along with various coal bands (Jeffrey, 2005a). “Particles that have been crushed to a size greater than their morphological features will merely get smaller without releasing their distinct components, and their densities will be comparable to those of the uncrushed particles” (Campbell *et al.*, 2017). Thus, it is important to sufficiently reduce the size of particles to enable the liberation of valuable minerals from the gangue while preventing the excessive formation of fines that may render the process uneconomic.

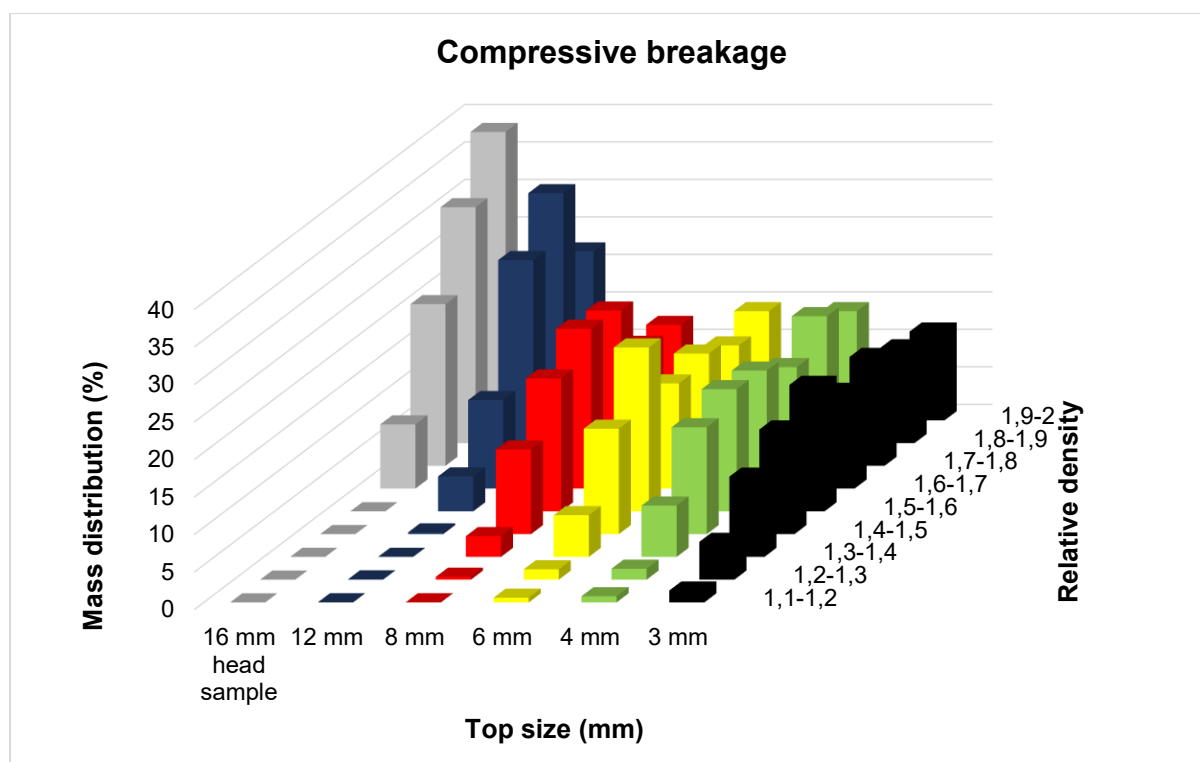


Figure 4.4: Density distribution of particles after compressive breakage of the 16 mm head sample to 3 mm top size.

After compressive breakage of the coal to a top size of 12 mm, there is a shift in the mass distribution towards the middlings products. Middlings are particles of locked mineral and gangue matter that require further liberation (Wills and Napier-Munn, 2006). A significant shift in the amount of particles can be observed from the dense particles RD interval of >1.8 to the middlings RD intervals of 1.6-1.8 after the coal sample was subjected to compressive crushing. There was about 14.2% (by mass) decrease in the proportion of near dense particles (from 70% to 55.8%) when the top size was reduced to 12 mm via compressive breakage. Middlings products proportion in the RD intervals of 1.6-1.8 was improved by 9.2% (by mass) (from 30% to 39.2%). Compressive breakage to 12 mm also resulted in a small amount (4.7% by mass) of particles of lower density middlings products of RD ranging between 1.5-1.6 not previously observed in the head sample.

As seen in

Figure 4.4, it was observed that after further size reduction to top size 8 mm there was an increase in the amount of particles shifting towards the middlings RD intervals (between 1.6 - 1.7). Particle size reduction to top 8 mm also resulted in the significant liberation of low-density clean coal material ($RD < 1.4$) as compared to crushing to 12 mm top size. These clean coal particles are desirable and are composed of vitrinite-rich coal macerals with little mineral

matter (in the case of Waterberg coalfield coal). About 3.2% (by mass) of the particles attained had $RD < 1.4$.

Compressive breakage to top size 6 mm resulted in a considerable decrease in the amount of coal middlings in the RD range of between 1.5 – 1.8 to lower density middlings products in the RD range 1.4 – 1.5. The increase in the liberation of the middlings products after further size reduction resulted in the increase the the amount of vitrinite rich clean coal ($RD < 1.4$). The proportion of the clean coal products doubled (increased from 3.2% to 7.6%) when the particles top size was reduced from 8 mm to 6 mm. The increase in the amount of clean coal particles observed at lower density may be due to the increased liberation of valuable coal macerals that was interlocked with the gangue matter in the middlings and dense coal particles.

As seen in

Figure 4.4, with compressive breakage to top size 4 mm there is a decrease in the amount of dense and middlings coal particles. A considerable decrease was observed in the RD interval 1.5-1.6 when the top size is reduced from 6 mm to 4mm. The proportion of particles in the 1.5-1.6 RD range was decreased from 21.8 to 16.5% (by mass). An increase in the amount of clean coal particles with $RD < 1.4$ was also observed when the top size was reduced to 4 mm. The latter was also observed when the top size was further reduced to top size 3mm. Size reduction to smaller top sizes increased the amount of clean coal particles while the number of middlings and dense material is reduced.

Figure 4.5 below shows the density distribution of the sample after each subsequent compressive breakage stage of the 16 mm head sample to 3 mm in the RD intervals 1.25, 1.55 and 1.85 respectively. As seen in Figure 4.5 compressive breakage to top size 12 mm had little effect on the liberation of low density coal products in the RD interval 1.25. However, there was a small increase (4.7% by mass) in the proportion of the middlings coal products in the RD interval of 1.55 while the bulk majority (33.3% by mass) of the coal particles was within the 1.85 RD interval. Particle top size reduction to 8 mm drastically decreased the proportion of high density coal particles (from 33.3% to 13.1% by mass) while a significant increase in the quantity of the middlings products was observed. i.e. the proportion of coal particles in the RD interval 1.55 increased from 4.7 to 17.7%. The gradual increase in the proportion of the middlings products was also observed when the top size was reduced to 6 mm. Compressive breakage to top size 6 mm also led to a small increase in the liberation of low density coal products from 0.4 to 1.4%. Small but progressive increase in the proportion of low density

products were also observed when the top size was reduced to 4 mm. Compressive breakage to 3 mm resulted in the highest proportion (5% by mass) of low density products.

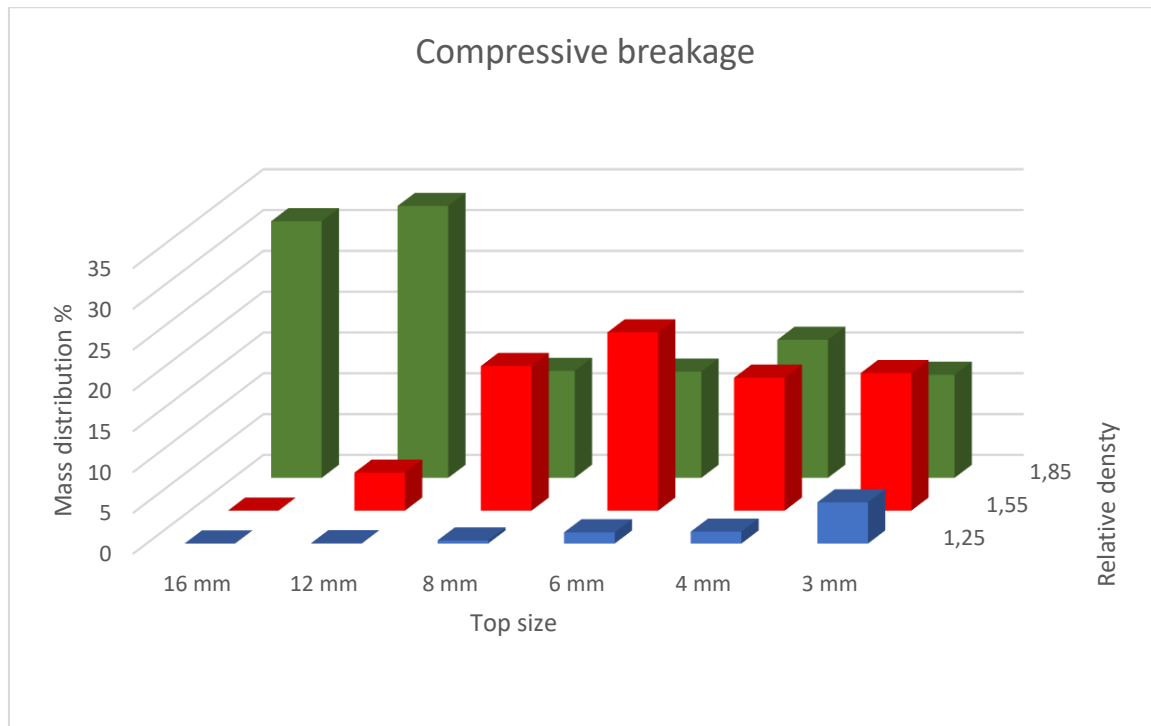


Figure 4.5 Density distribution of particles in RD interval 1.25, 1.55 and 1.85 after compressive breakage of the 16 mm head sample to 3 mm

4.3.2. Impact breakage

Figure 4.6 shows the results of the impact breakage tests. It shows the density distribution of each sample after it has been broken down to a specific top size, i.e. one distribution for each top size from 16 mm to 3 mm. As previously reported in section 4.3.1, the 16 mm head sample is mainly composed of near dense coal and middlings products. As seen in Figure 4.6, the initial size reduction to top size 12 mm through impact breakage decreased the proportion of the near dense products and increased the quantity of the middlings products. A significant increase in the proportion of particles in the RD interval 1.4-1.5 was observed when the head sample was subjected to impact breakage to top size 12 mm. Unlike compressive breakage, impact crushing of the head sample to top size 12 mm resulted a small liberation of low-density clean coal particles (RD < 1.4). About 1.7% (by mass) clean coal products were obtained after impact breakage to top size 12 mm.

As seen in figure 4.6, impact breakage to top size 8 mm further decreased the proportion of high-density coal and middlings products and increased the quantity of low-density clean coal particles. A considerable decrease in the proportion of middlings products was observed in the RD range of 1.7-1.8 when the top size was reduced from 12 to 8 mm. The proportion of particles in the RD interval 1.7-1.8 was reduced from 38.1 to 11.2% (by mass). This considerable shift in the proportion of these middlings products resulted in increased quantity of lower density middlings products of RD between 1.4-1.6. The proportion of vitrinite-rich low-density clean coal products (RD < 1.4) was significantly increased when the top size was reduced to 8 mm. About 6.4% (by mass) of the particles obtained had RD of less than 1.4.

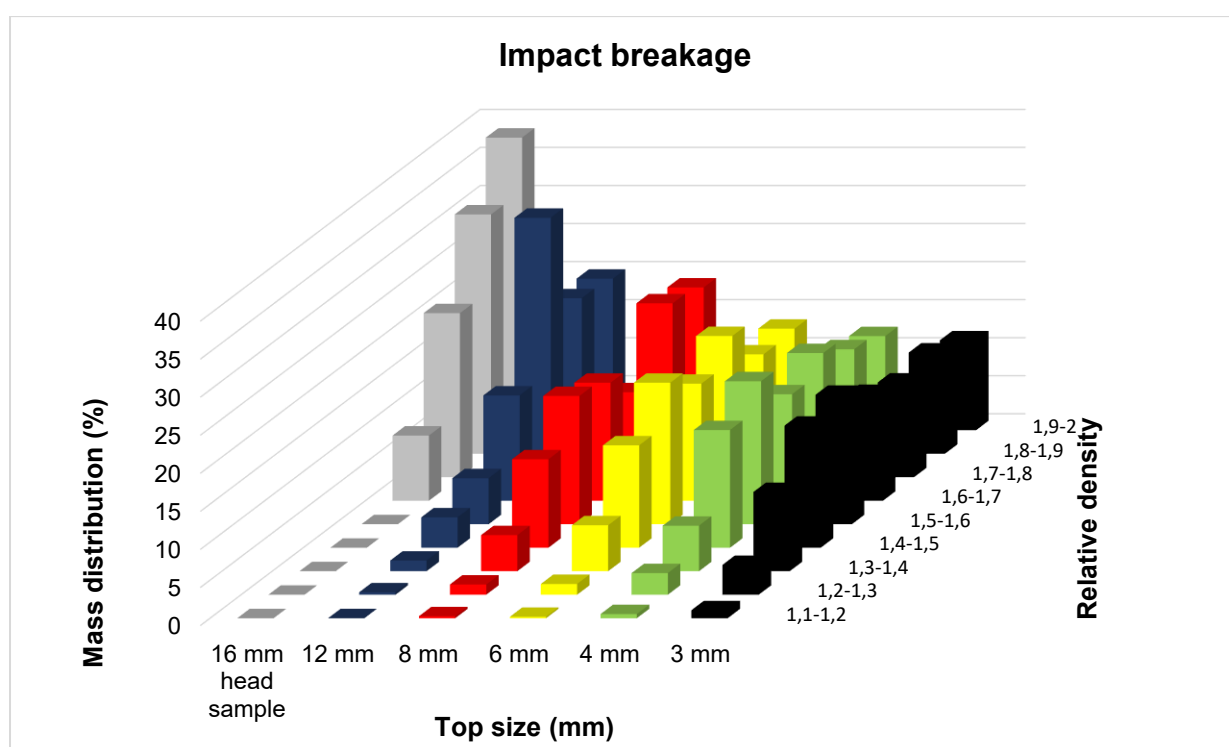


Figure 4.6: Size by washability graph of impact breakage 16 mm head sample to 3 mm top size.

As seen in Figure 4.6, size reduction to top size 6 mm also led to a decrease in the proportion of dense and middlings products while the quantity of clean coal particles (RD < 1.4) was increased. The latter was also observed when the top size was reduced to 4 mm and 3 mm. Crushing to small particle sizes reduced the amount of high dense and middlings products while increasing the number of low-density clean coal particles. There is a continuous increase in coal liberation with a decrease in the particles top size. Crushing to smaller top sizes may have liberated the locked coal macerals trapped in dense coal particles and thus improved the liberation of the coal.

Figure 4.7 below shows the density distribution of the sample after each subsequent impact breakage stage of the 16 mm head sample to 3 mm in the RD intervals 1.25, 1.55 and 1.85 respectively. As seen in Figure 4.7, there was a significant decrease in the proportion of high density particles (RD interval 1.85) when the coal sample was impact crushed to top size 12 mm. i.e. the proportion of particles in the RD interval 1.85 decreased from 31.4 to 20.4% (by mass) when the top size was reduced to 12 mm. A small increase (6% by mass) in the proportion of the middlings products was also observed. Impact breakage to top size 12 mm had a very small effect on the liberation of low density coal products in the RD interval 1.25. Impact breakage to top size 8 mm significantly increased the proportion of the middlings products from 6 to 16.9% (by mass). A small increase (from 0.3 to 1.3% by mass) in the proportion of low density product was also observed after impact crushing to top size 8 mm. Gradual improvements in the liberation of low density and middlings products was observed when the top size was reduced to 6 mm and 4 mm. Impact breakage to top size 3 mm resulted in the highest proportion of low density coal products. This shows that crushing to smaller top sizes increased the liberation of the coal from the mineral matter and improved the coal quality.

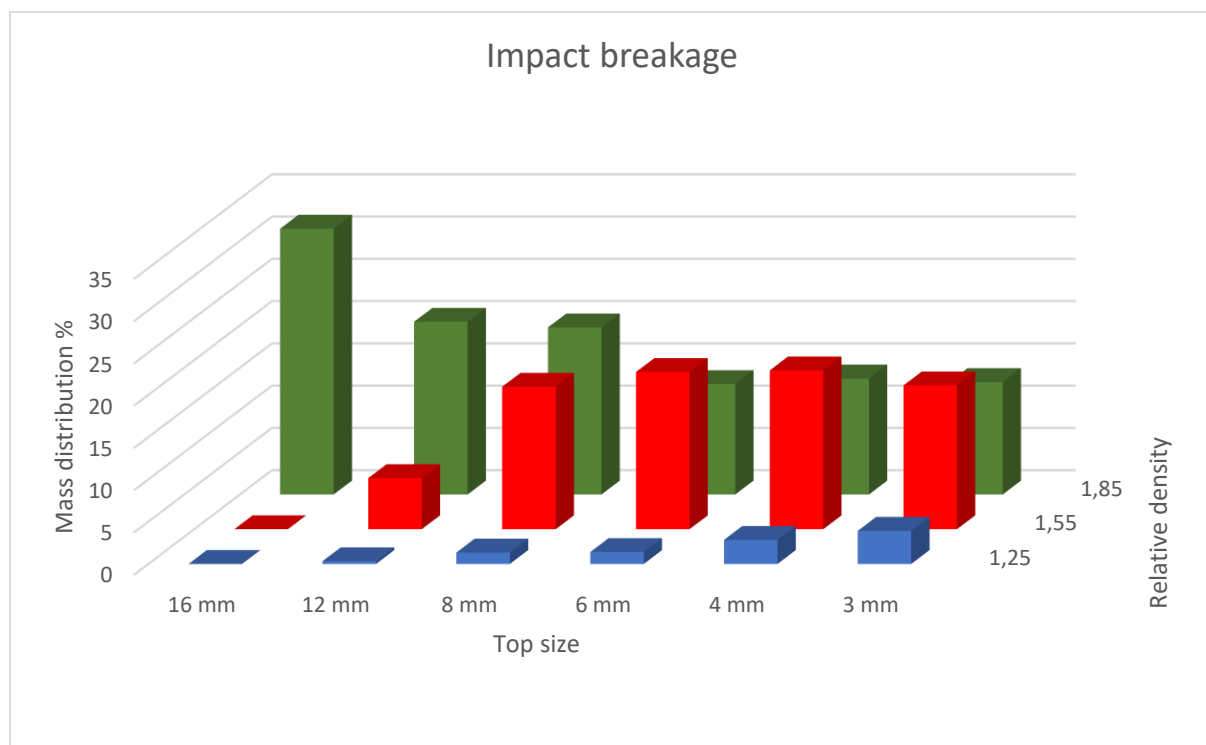


Figure 4.7: Density distribution of particles in RD interval 1.25, 1.55 and 1.85 after impact breakage of the 16 mm head sample to 3 mm

4.3.3. Waterberg coalfield coal washability curves

4.3.3.1. Compressive breakage washability curves

Figure 4.8 shows the progressive changes in the densimetric curves for compressive breakage as the top size is reduced. The curves show the cumulative mass yield of each sample after crushing to different top sizes. Although the initial crushing of the coal lump using a jaw crusher may have resulted in some liberation, the densimetric curve shows that the 16 mm head sample was mainly composed of middlings and dense products and that further size reduction was required to liberate the coal. As seen from Figure 4.8, after the initial compressive breakage to top size 12 mm, there is a small increase in the cumulative mass yield at RD interval 1.6. Compressive breakage to top size 12 mm however, had negligible effect on the liberation of clean coal products of $RD < 1.4$. Compressive breakage to top size 12 mm however, did increase the cumulative mass yield middlings products RD intervals (between 1.5 – 1.8).

As it can be seen from Figure 4.8, further size reduction by compressive breakage to top size 8 mm significantly increased the cumulative mass yield of the coal products at different RD intervals. Compressive breakage to top size 8 mm significantly increased the liberation of clean coal products at lower RD intervals 1.2 – 1.4. When comparing compressive breakage to top sizes of 12 mm and 8 mm, there was a significant increase in the cumulative mass yield of low density clean coal products ($RD < 1.4$) by crushing the coal to a smaller top size (8 mm). i.e. at RD interval 1.4 the cumulative mass yield increased from 0.3% to 14.4% when the coal was crushed to 8 mm. Crushing to top size 8 mm may have exposed and liberated more low-density coal products that were trapped with the mineral matter. Compressive breakage to top size 8 mm was more effective in the liberation of the pure macerals from the heavy dense minerals when compared to top size 12 mm.

As seen from Figure 4.8, compressive breakage to top size 6 mm increased the cumulative mass yield of lower density ($RD < 1.4$) products. Size reduction from 8 to 6 mm, the cumulative mass yield increased from 14.4% to 21.6% at RD 1.4. Size reduction from top size 8 mm to 6 mm improved the mass yield at RD interval 1.4 by 7.2%. Similar to top size 8 mm, size reduction to top size 6 mm also improved the mass yield of the middlings products. It can be seen from Figure 4.8 that there is a small improvement in the mass yield when the top size is reduced from 6 mm to 4 mm at RD interval 1.4. Small increase in the mass yield of low-density clean coal was also observed when the top size is reduced from 4 mm to 3 mm.

Crushing the coarse coal from 16 mm to a smaller size 3 mm improved the mass yield of low-density clean coal products ($RD < 1.4$). Significant improvement in the liberation of clean coal products and the cumulative mass yield by crushing the coal top size 8 mm. Progressive but smaller improvements in the mass yield of clean coal products were observed when the top size was reduced from 8 mm to 3 mm.

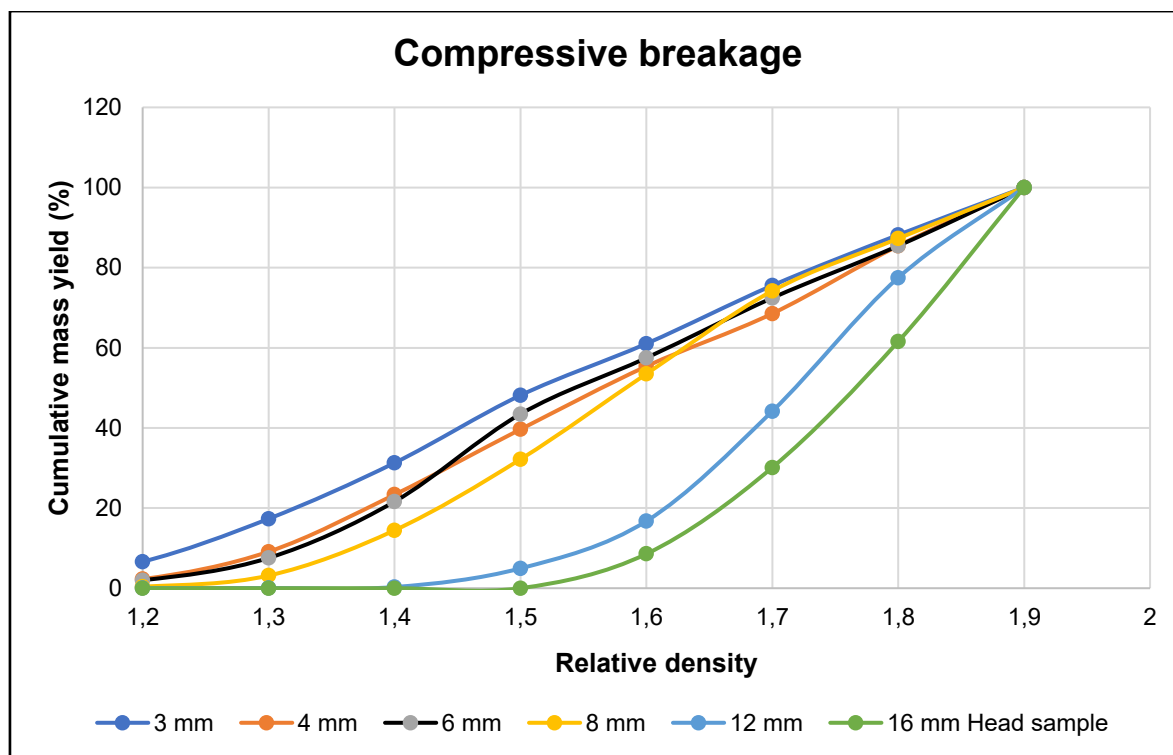


Figure 4.8: Densimetric curves for compressive breakage to different top sizes

Table 4.2 below shows the cumulative yield trend of the different coal products (clean coal, middlings and high density/dense coal) after compressive breakage to different top sizes. The head sample (16 mm) has nearly no clean coal products and is predominantly composed of middlings (60%) and high density (40%) coal products. Studies have shown that the Waterberg coals contain a high proportion of reactive macerals and mineral matter content. This contributes to the formation of middlings and high-density fractions during beneficiation processes. The yield of low-density clean coal products was significantly improved when the top size was reduced to between 8 and 6 mm. The yield of low-density clean coal was significantly improved to about 15% after compressive breakage to 8 mm and to around 20% after top size reduction to 6 mm. Top size reduction to 3 mm resulted in the highest mass yield of low-density clean coal products at 32%.

The cumulative mass yield of the middlings products changes with a reduction in the particle's top sizes. As compared to coarser sizes, the yield of the middlings products increases for

smaller sizes showing that more material is being recovered in the low-density clean coal fraction. On the other hand, the yield of high-density coal products decreases significantly when the coal is crushed to smaller top sizes. The mass yield of high-density coal products decreased from 40% to 18% when the particle top size was reduced from 16 mm to 3 mm. The decrease in the yield of high-density coal products shows effective liberation of the valuable coal products from the gangue with crushing to smaller sizes.

Table 4.2: Yield trend of the different coal products after compressive breakage to different top sizes

Top Size (mm)	Low-Density Coal Yield (<1.4)	Middlings Yield (1.4 - 1.8)	High density coal Yield (>1.8)
16 (Head)	0%	60%	40%
12	3%	47%	50%
8	15%	50%	35%
6	20%	52%	28%
4	25%	53%	22%
3	32%	50%	18%

4.3.3.2. Impact breakage washability curves

Figure 4.9 shows the progressive changes in the densimetric curves after impact breakage as the top size is reduced. The curve shows the cumulative mass yield of each sample at different top sizes and RD. As previously discussed, there's no material in the lower density intervals (RD < 1.4) of the head sample of top size 16 mm. After the head sample was subjected to impact breakage and reduced to top size 12 mm, there was a slight increase in the cumulative mass yield of low density material between RD 1.3 -1.4. The proportion of dense materials was decreased and there was substantial increase in the amount of middlings products (between RD 1.5 – 1.7). Subsequent top size reduction from 12 mm to 8 mm significantly increased the mass yield of low density clean coal products. This resulted in the liberation of more pure coal macerals trapped within the middlings products of the crushed 12 mm coal.

i.e. particles top size reduction from 12 mm to 8 mm increased the cumulative mass yield of low-density clean coal from 5.7% to about 18% (12% yield improvement) after impact breakage. At RD interval 1.5, the cumulative mass yield of the middlings products was significantly improved (from 11.7% to 34.8%) when the top size was reduced from 12 mm to 8 mm by impact breakage.

A small increase (from 18% to 21.1%) in the mass yield of low-density coal was observed when the top size was reduced to 6 mm at RD interval 1.4. However, there is significant increase in the proportion of material between RD intervals 1.5 – 1.7 when crushing from 8 mm to top size 6 mm. This may be due to the increased liberation of gangue matter at smaller top sizes. Further size reduction from 6 mm to 4 mm resulted in a small increase (from 21.1% to 24.8%) in the cumulative mass yield low-density clean coal at RD interval 1.4. There was an insignificant change in the mass yield at RD > 1.5 by crushing to top size 4 mm. Subsequent size reduction from top size 4 mm to 3 mm further improved the mass yield of low-density coal products (from 24.8% to 31.4%) at RD interval 1.4.

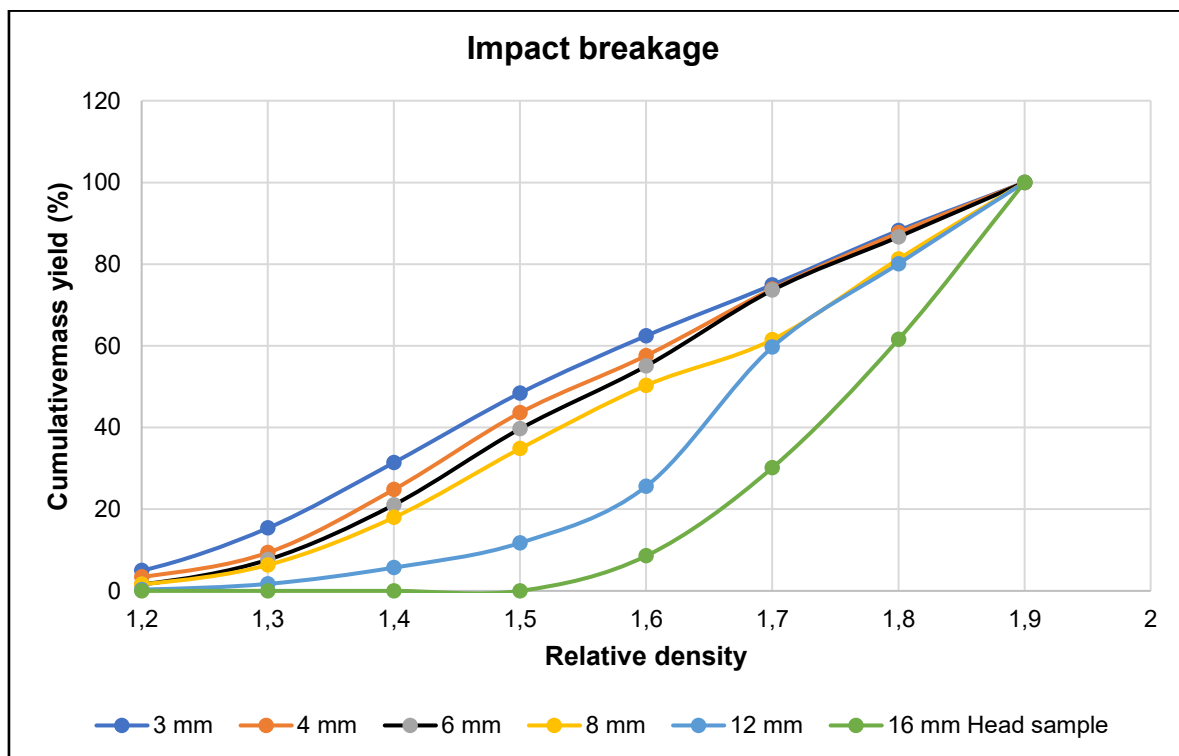


Figure 4.9: Densimetric curve for impact breakage to a top size of 3 mm.

Table 4.3 shows the changes in the cumulative mass yield of the coal products (low-density clean coal, middlings and high density) after impact breakage to different top sizes. Crushing the coal to smaller top size 3 mm resulted in the highest mass yield of low-density clean coal (35%) as compared to the coarse 16 mm coal sample. Significant improvements in the mass

yield of low-density clean coal products were observed when the coal was subjected to impact breakage to top sizes 8 and 6 mm. The yield of the low-density coal products was 25% after crushing to 8 mm and 28% after breakage to 6 mm.

The mass yield of the middlings products decreases with the reduction in the particles top size. Compared to the head sample (16 mm), top size reduction to 3 mm decreased the middlings fraction from 60% to 45%. This is due to the liberation of the middlings products in the coarse sample into the low-density clean coal fraction. The mass yield of high-density coal products was reduced from 40% to 20% when the top size was reduced from 16 mm to 3 mm. The decrease in the mass yield of high-density coal products after every subsequent top size reduction stage indicates that crushing to smaller size is the most effective method in separating coal from dense minerals.

Table 4.3: Yield trend of the different coal products after impact breakage to different to sizes

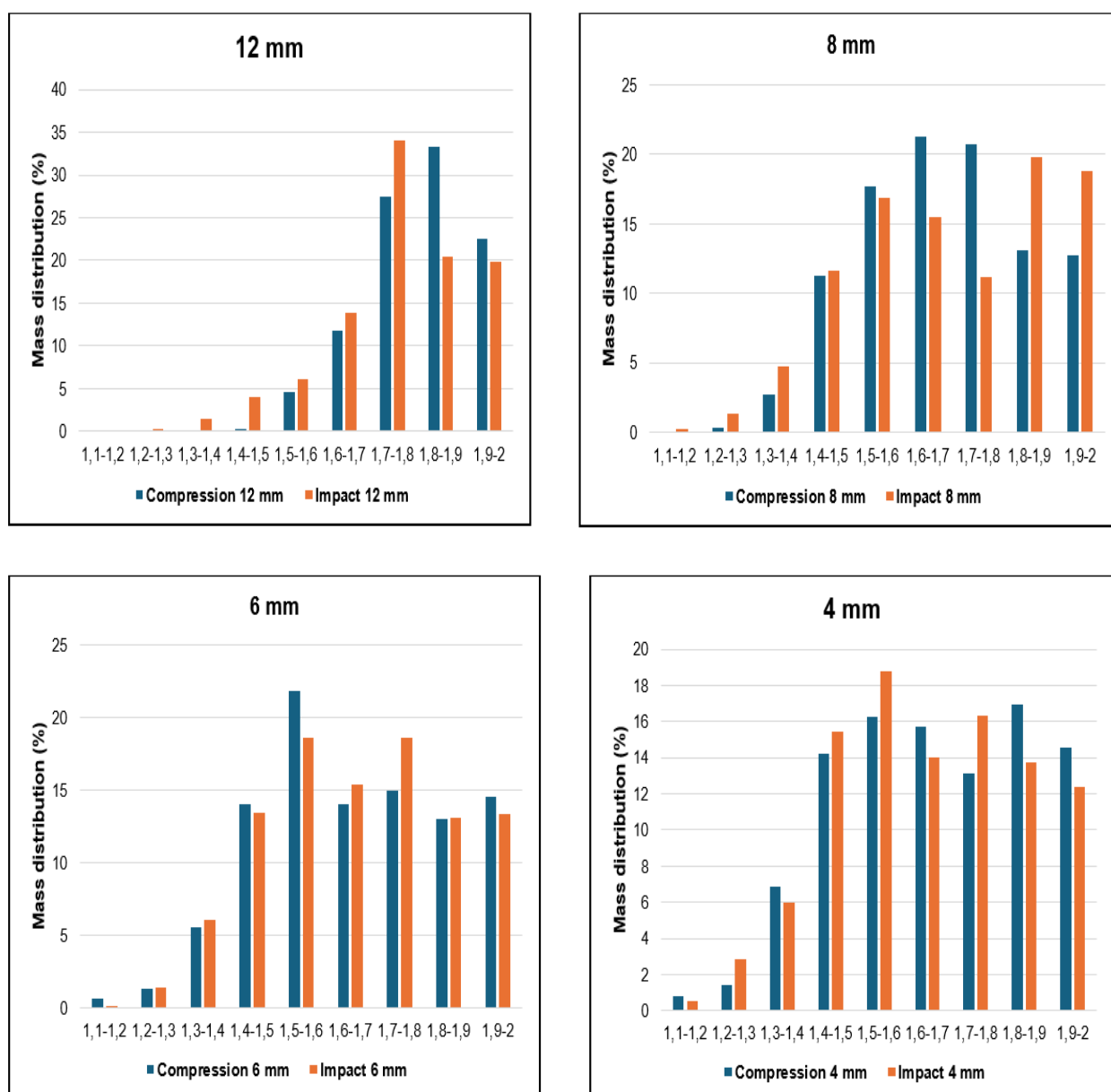
Top Size (mm)	Low-Density Coal Yield (<1.4)	Middlings Yield (1.4 - 1.8)	High-Density Yield (> 1.8)
16 (Head)	0%	60%	40%
12	5%	55%	40%
8	25%	47%	28%
6	28%	47%	25%
4	32%	46%	22%
3	35%	45%	20%

4.3.4. Compressive and impact breakage comparison

4.3.4.1. Compressive and impact breakage mass distribution comparison

Figure 4.10 compares the mass distribution vs density data of after compressive and impact breakage to different top sizes. It can be seen from Figure 4.10 that impact breakage to top size 12 mm resulted in the least proportion of high-density particles (RD> 1.8), about 40.2% (by mass) as compared to compressive breakage at 55.8% (by mass). Impact breakage to top

size 12 mm resulted in highest proportion of middlings products (57.8% by mass) in the RD ranges 1.4-1.8 when compared to compressive breakage (44.1 by mass). The majority of the particles obtained after compressive breakage to top size 12 mm were relatively dense (RD between 1.8-2). Impact breakage of the head sample to top size 12 mm released a small amount of clean coal particles of RD < 1.4. As seen from Figure 4.10, negligible proportion of low-density clean coal products (RD < 1.4) was observed when the head sample was subjected to compressive breakage to top size 12 mm.



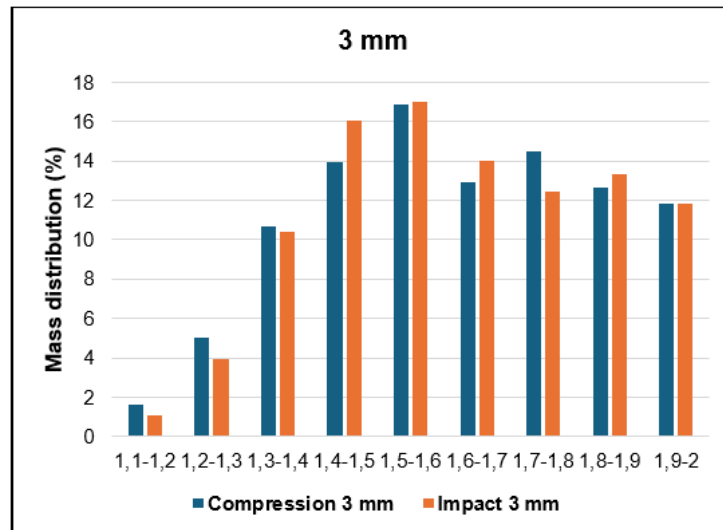


Figure 4.10: Mass distribution vs density comparison of compressive and impact breakage at different top sizes.

Compressive and impact breakage of the coal from top size 12 to 8 mm decreased the proportion of dense and middlings coal products. Compressive breakage to top size 8 mm resulted in high proportion of middlings products in the RD range 1.4-1.8 as compared to impact breakage. High proportion of dense coal particles (RD between 1.8-2) were observed after impact breakage to top size 8 mm. However, impact breakage to top size 8 mm resulted in the highest amount of low-density clean coal products (RD < 1.4) when compared to compressive crushing after the top size was reduced to 8 mm. About 6.3% of the particles had RD < 1.4 after impact breakage to 8 mm as compared to 3.4% (by mass) after compressive crushing. Further size reduction from 8 to 6 mm increased the proportion of low-density clean coal products in both breakage modes. The proportion of low-density clean coal products increased from 3.4 to 7.55% after compressive breakage to 6 mm and from 6.3 to 7.62% (by mass) in the case of impact breakage. There is negligible difference in the proportion of clean coal products (RD < 1.4) obtained after compressive and impact breakage to top size 6 mm. The latter was also observed when the top size was further reduced to 4 mm. However, compressive breakage to top size 6 mm resulted in the highest amount of low dense middlings products in the RD interval 1.5-1.6 as compared to impact crushing.

Crushing to smaller top size of 3 mm resulted in a decrease in the proportion of dense and middlings coal products and an increase in the amount of low-density clean coal products in both breakage modes. There is a small difference in the proportion of low-density clean coal products obtained after compressive and impact breakage to top size 3 mm. About 17.3% of the particles had RD of less than 1.4 after compressive breakage to 3 mm as compared to

15.4% (by mass) coal products after impact breakage. In both breakage modes, crushing to smaller top sizes increased the proportion of low-density clean coal products.

Figure 4.11 shows density distribution comparisons after compressive and impact breakage of the 16 mm head sample to top size 3 mm at RD intervals 1.25, 1.55 and 1.85. As seen in Figure 4.11, impact breakage of the 16 mm head sample to top size 12 mm resulted in the lowest proportion (20.3% by mass) of high density (near dense) coal products as compared to compressive crushing (33.3% by mass). Impact breakage to top size 12 mm resulted in the highest proportion (6% by mass) of the middlings products in the RD interval 1.55 as compared to that of compressive breakage (4.7% by mass). Further top size reduction to 8 mm significantly increased the proportion of the middlings products after compressive and impact breakage. There is a small difference in the proportion of the middlings products after compressive and impact breakage. About 17.7% (by mass) middlings products were obtained after the top size was reduced to 8 mm via compressive breakage as compared to 16.8% (by mass) attained through impact breakage. Compressive breakage to top size 8 mm had no significant effect on the liberation of low-density products whereas a small proportion (1.3% by mass) of clean coal products (RD 1.25) was observed after impact crushing to 8 mm.

Top size reduction to 6 mm increased the proportion of the middlings products while the number of high-density particles decrease for both breakage modes. Compressive breakage resulted in the highest proportion (21.8% by mass) of middlings products as compared to impact crushing (18.6% by mass). Compressive breakage to top size 6 mm significantly improved the liberation of low-density products (from 0.4% to 1.4% by mass) whereas there is negligible difference in the proportion of low-density products when the top size was reduced from 8 mm to 6 mm via impact crushing. Compressive breakage to top size 4 mm resulted in the lowest proportion (16.3% by mass) of middlings products as compared to when the top size was reduced to 8 mm and 6 mm. There is a gradual increase in the proportion of the middlings and low-density coal products when the particle top size was reduced to 4 mm via impact breakage. Compressive breakage to 3 mm resulted in the highest proportion (5% by mass) of low-density coal products as compared to impact crushing (3.9% by mass). Although the difference between the two breakage modes is small, this indicates that at smaller sizes, compressive breakage may be more effective in liberating coal macerals, due to fracture propagation along bedding planes and mineral boundaries. Peng and Chiang (1984), reported that compressive forces at fine sizes promote interfacial breakage, improving selective liberation.

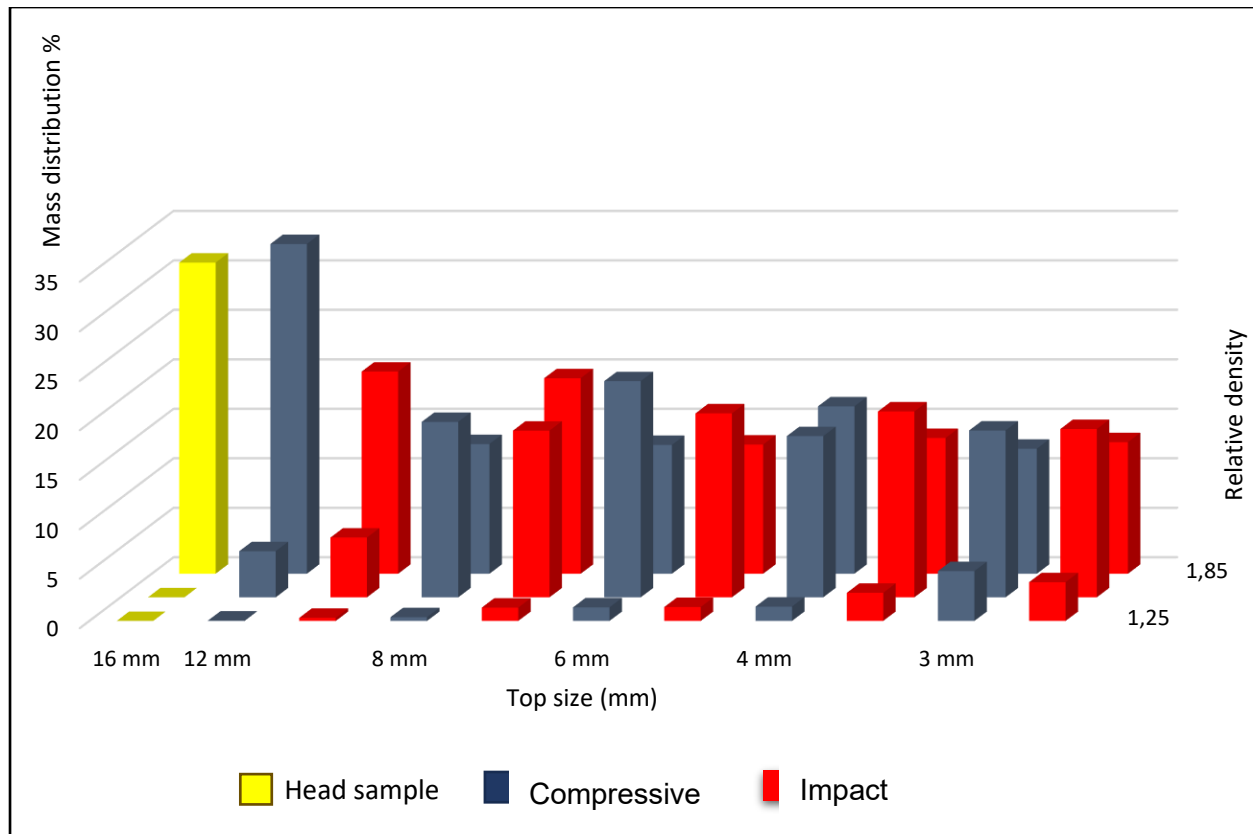


Figure 4.11: Density distribution comparison after compressive and impact breakage of the 16 mm head sample to 3 mm at RD intervals 1.25, 1.55 and 1.85

4.3.4.2. Compressive and impact breakage cumulative yield comparison

When comparing compressive and impact crushing, it can be seen from Figure 4.8 and Figure 4.9 that there was a small increase in the cumulative mass yield of low-density clean coal products at RD 1.4 after impact crushing (5.7%) when the head sample was reduced to top size 12 mm. Compressive breakage to 12 mm did not bring about any significant improvement (0.3%) to the mass yield of low-density coal products (RD < 1.4). When the particles sizes were further reduced from 12 mm to 8 mm, the mass yield of low-density clean coal products at RD interval 1.4 was significantly increased for both breakage modes while impact breakage liberated more clean coal macerals at the same top size. The mass yield of the low-density coal products was increased from 5.7-18% for impact breakage and from 0.3-14.4% in the case of compressive breakage. Potgieter (2017), who observed that impact breakage at moderate top sizes improves liberation due to rapid, high-energy fracture propagation through weaker coal phases

Further size reduction from 8 mm to 6 mm resulted in a small increase in the cumulative mass yield of low-density products. The yield of low-density clean coal products was improved from 18-21.1% after impact breakage and from 14.4-21.7% in the case compressive breakage. This shows that at smaller particle sizes, the difference between the two breakage modes decreases as most of the easily accessible coal macerals have been liberated. Reducing the top size from 6 mm to 4 mm did not have any significant effect to the mass yield after compressive breakage. However, there was a small increase in the mass yield of low-density products ($RD < 1.4$) was observed after impact breakage of the coal. As seen from figures 4.8 and 4.9, particle size reduction using compressive and impact breakage modes reduced the proportion of dense material; contributed to the liberation of coal macerals from the gangue and increased the cumulative yields of low density ($RD < 1.4$) products.

A certain particle size is usually required by coal users in order to support downstream uses. From the above, it can be deduced that crushing to top size 8 mm significantly increased the liberation of the coal macerals from the gangue and improved the mass yield of low-density clean coal products of $RD < 1.4$. An increase in the mass yield was also observed when the top size was reduced to 6 mm. Crushing to top size 4 mm had little effect on the mass yield. Crushing to top size of 3 mm did improve coal liberation however, crushing to small particle sizes may result in the excessive formation of fines. Fines are reportedly difficult to handle and may require unique beneficiation techniques such as dewatering equipment that may render the process uneconomical (Noble and Luttrell, 2015). From Figure 4.8 and Figure 4.9, it can be seen that the optimal particle sizes that greatly influenced the mass yield of low-density clean coal products in both breakage modes was when the coal was crushed to top sizes 8 mm and 6 mm. This is in agreement with results from other studies, which show that increasing breakage along mineral boundaries through particle size reduction increases the proportion of low-density clean coal that is liberated (Potgieter, 2019; Sehlabaka, 2021). In order to determine the most suitable breakage mode and top size combination, the two breakage modes and the above-mentioned optimal sizes were compared.

Figure 4.12 shows the difference in the cumulative mass yields after compressive and impact breakage at top sizes 8 mm and 6 mm. From Figure 4.12, it can be seen that compressive breakage to top size 8 mm resulted in the lowest mass yields of low-density coal products of $RD < 1.4$. At top size 8 mm, impact breakage resulted in high mass yields of coal material with $RD < 1.4$. However, compressive breakage of the coal to top size 8 mm produced more middlings products in the RD range 1.6–1.7 when compared to impact breakage at the same top size. Further size reduction from 8 mm to 6 mm shows a small increase in the mass yield in both breakage modes. Between RD intervals 1.2–1.4, there is an insignificant difference in

the mass yields of clean coal products ($RD < 1.4$) obtained through compressive and impact breakage when the top size was reduced from 8 mm to 6 mm. There is a small difference in the mass yield between RD intervals 1.5–1.6 in favour of compressive breakage. There is an insignificant difference in the cumulative mass yields of the coal products between RD intervals 1.7–1.9 of compressive crushed 8 mm and 6 mm and impact crushed 6 mm particles. Impact breakage to top size 8 mm resulted in the lowest mass yields of middlings products in the RD range 1.6–1.8.

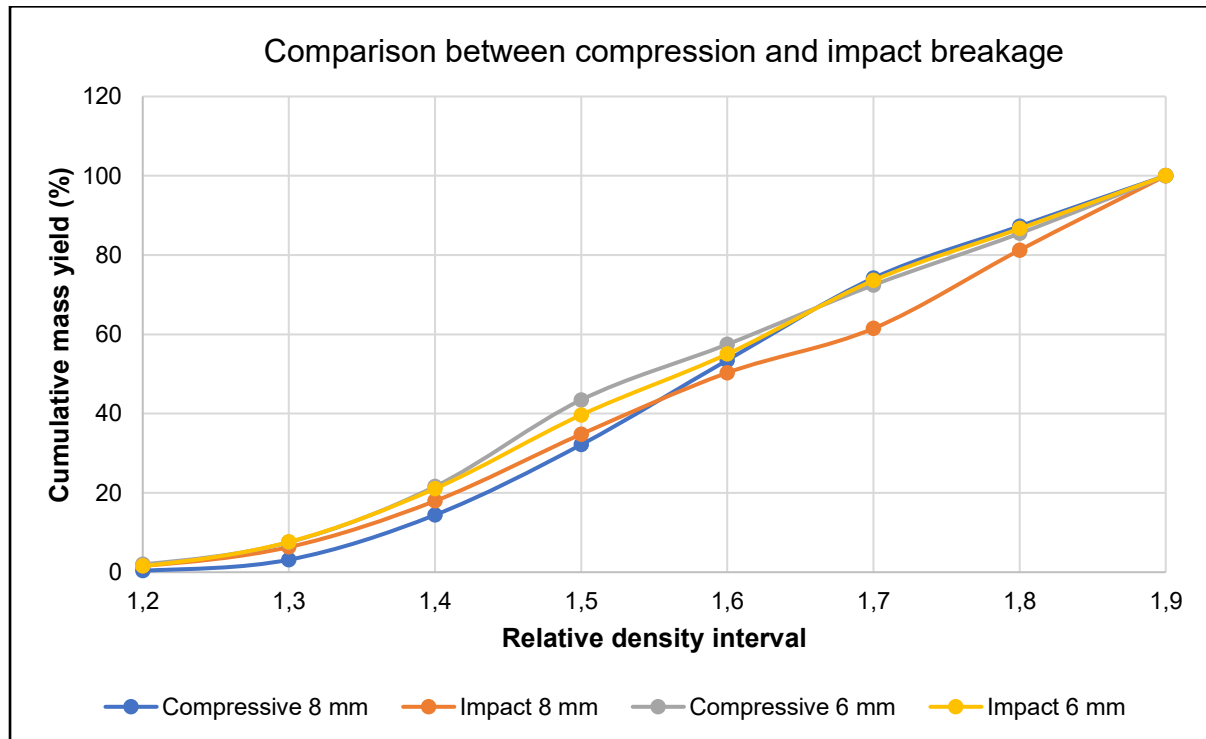


Figure 4.12: Comparison between compressive and impact breakage at top sizes 8 and 6 mm.

Table 4.4 shows the change in the mass yield after the 16 mm head sample was subjected to compressive and impact breakage at different top sizes. Assuming a density cutpoint of 1.4, there is a small increase in the mass yields when the head sample is subjected to compressive and impact breakage to top size 12 mm. Size reduction from 12 mm to 8 mm significantly improved the mass yield after compressive and impact breakage. At the density cutpoint 1.4, the mass yield increased from 0.28 to 14.4% after compressive breakage and from 5.7 to 17.9% in the case of impact breakage. Further size reduction from 8 mm to 6 mm also improved the mass yield for both breakage modes. The mass yield improved by 7.2%, from 14.4 to 21.6% when the coal was compressive crushed to 6 mm and by 3.2% in the case of impact breakage. There was a small difference of 0.6% in the mass yield in favour of compressive breakage when the coal was crushed to 6 mm. There was a small increase in the mass yield when the coal was crushed to 4 mm for both breakage modes. Crushing to

smaller top particle size of 3 mm also resulted in improvements in the mass yield. The mass yield increased from 23.3 to 31.3%, an increment of 8% after compressive breakage to 3 mm. Impact breakage to 3 mm increased the mass yield from 24.8 to 31.4%, improving the yield by 6.6%. There is no significant difference in the mass yield of coal products obtained at top size 3 mm after compressive and impact breakage.

Table 4.4: Mass yield comparison after compressive and impact breakage of the head sample to 3 mm at cutpoint 1,4.

Top size (mm)	Mass yield % after Compressive breakage at RD cutpoint 1,4	Mass yield % after Impact breakage at RD cutpoint 1,4	Mass yield % difference between breakage modes
16 head sample	-	-	-
12	0,28%	5,7%	5,4% impact
8	14,4%	17,9%	3,5% impact
6	21,6%	21,1%	0,5% compressive
4	23,3%	24,8%	1,5% impact
3	31,3%	31,4%	0,1% impact

As it can be seen from figures 4.7, 4.8, 4.10 and table 4.2, impact breakage was the more effective method in the liberation of coal and greatly improved the cumulative mass yield of the clean coal. Similar findings were made in the study by Campbell *et al.*, (2017) where the effect of mode and top size of applied breakage on coal yield was investigated. In the study the effect of breakage modes combination that includes compression, impact and attrition on Moatize ROM coal from Mozambique at top sizes 13.2 and 6.7 mm was studied (Campbell *et al.*, 2017). Like coal from the Waterberg coalfields, ROM Moatize coal from Mozambique has a highly layered morphological structure of coal bands intercalated with mineral matter. It was reported that compressive and impact breakage to top size 13.2 mm did not have any significant effect on the mass yield (Campbell *et al.*, 2017). However, the mass yield was significantly improved when the coal was crushed to top size 6.7 mm (Campbell *et al.*, 2017).

Impact breakage resulted in higher coal yields of material with a RD of less than 1.4 (Campbell *et al.*, 2017). The increase in the coal yield was attributed to the increased exposure of valuable coal macerals by impact breakage and increased liberation of brittle vitrinite-rich fraction for attritioning (Campbell *et al.*, 2017).

For both breakage modes, there is progressive but small improvement in the mass yield of clean coal products when the top size was reduced below 6 mm. This is because small particles are resistance to breakage and tend to undergo plastic deformation when crushed necessitating the need of repetitive applied forces. Unlike coarse particles, small particles contain little impurities and cracks that may render the particle friable. As particle top size decreases (6 mm, 4 mm, 3 mm), the difference between compressive and impact crushing is reduced, indicating that the crushing method has less influence on the coal yield at finer sizes. This is consistent with findings from Potgieter (2017) who observed that below 4.75 mm both breakage methods achieved effective liberation. According to Peng and Chiang (1984), fracture mechanics and breakage energy distribution become less dependent on the type of loading below a particular size threshold since the particles are already close to the liberation limit.

The low coal yields from compressive breakage when compared to impact crushing may be attributed to the direction of the applied forces. As explained in the previous chapter (chapter 3) section 3.3.2.2, the 80 kg lawn roller was rolled over the sample from the right to the left exerting a parallel uniaxial compressive force onto individual coal particles. Viljoen *et al.*, (2014) studied coal degradation using micro-focused computed tomography. Bright-dull banded lithotype coal sample from Waterberg coalfields were subjected to compressive forces and the load was applied perpendicular and parallel to the bedding. It was reported that the direction of the applied load greatly influenced the expansion of existing cracks and the dissemination of newly formed cracks (Viljoen *et al.*, 2014).

4.4. Industrial applications

International and domestic coal standards requires that the coal must be washed and properly sized to conform set specifications before use. Crushing and sizing of ROM coal is an important step necessary to liberate the coal from the mineral matter for further processing. This step improves the coal quality and produces a coal product that is suitable for domestic and international industry applications.

Experimental data from this study show that for industries such as steel making (metallurgical coal) or export market where high quality/low-density clean coal is required, the coal should

be crushed between 8 to 3 mm. Crushing to smaller sizes liberated more of the lower density clean coal material and improved their mass yield. i.e. crushing between 8 to 3 mm yield approximately 25-35% of the low-density clean coal products as compared to 5% attained after impact breakage to 12 mm. These results are consistent with findings by Potgieter (2017), who demonstrated that breakage to smaller sizes, particularly around 4.75 mm led to a significant increase in clean coal yield ($RD < 1.4$). Although crushing to smaller sizes (up to 3 mm) enhanced the liberation of low-density clean coal products and improved their mass yields, crushing to smaller sizes can lead to excessive fines generation and can offset the benefits of the improved liberation. Therefore, it is important to find the ideal balance where the benefits between improved coal liberation outweighs costs and operational challenges associated with fines. Significant improvements in the mass yield of low-density clean coal products were obtained when the coal was crushed to between 8 and 6 mm. Small but progressive improvements were observed after crushing below 6 mm. To maximize the recovery of low-density clean coal without necessarily generating excessive fines, coal from the Waterberg coalfield should ideally be crushed to between 8- and 6-mm. However, the ideal size would also depend on the plant economics, costs associated with the handling of fines and downstream processing.

Compressive breakage to top size 6 and 4 mm resulted in the highest mass yield of middlings at 52% and 53% respectively. This indicates that while crushing to smaller improves the liberation of low-density coal, it simultaneously increases the proportion of the middlings products. Potgieter (2017) reported similar results, reporting that crushing to intermediate sizes (~4.75 mm) led to a substantial accumulation of material within the RD range of 1.5–2.0, especially under compressive stresses. Additionally, Sehlabaka (2021) observed that, at moderate top sizes, compressive breakage promotes microcracking without completely removing mineral inclusions. For impact breakage, the highest mass yield of middlings products (55%) was obtained after top size reduction to 12 mm. However, at coarser sizes, the coal is of lower quality and is associated with high ash. As a result, the ideal top size of middlings products use in industrial processes will depend on its ash content tolerances. High density coal products are mostly dominant at coarse particle sizes, and their mass yield is reduced substantially by crushing to smaller top sizes. These products can be used in mine fills. Table 4.5 summarises possible industries in which the investigated coal top sizes can potentially be used.

Table 4.5: Industry application of different coal products

Top size (mm)	Relative density interval	Fraction description	Industry
12	1.1-1.4	Clean coal	Poorly liberated, re-crushing of the coal required.
	1.4-1.7	Middlings	Domestic power generation.
	1.7-2	High density (dense) coal	Dominant in the coal samples. Utilised in mine backfilling or waste streams.
8 - 6	1.1-1.4	Clean coal	Domestic thermal use, coking coke and middlings recovery
	1.4-1.7	Middlings	Flotation feed, domestic power generation, cement kilns
	1.7-2	High density (dense) coal	Mine filler, ash recovery
4 - 3	1.1-1.4	Clean coal	Pulverised coal injection, export grade thermal coal, metallurgical coal.
	1.4-1.7	Middlings	Industrial boilers, slurry fuel.
	1.7-2	High density (dense) coal	Cement additive.

4.5. Effect of breakage mode and top size on particle shape

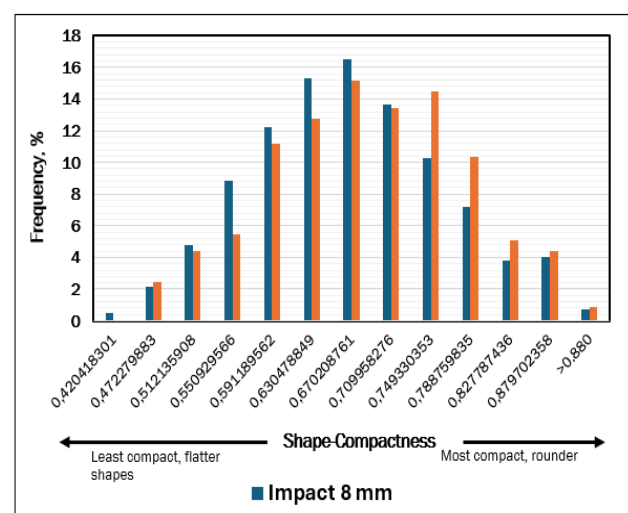
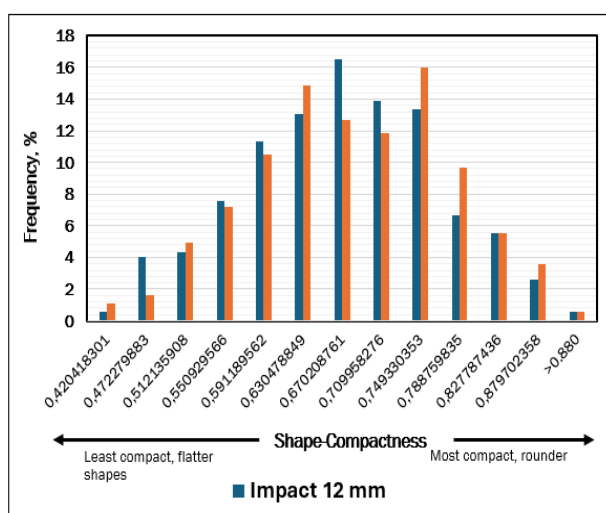
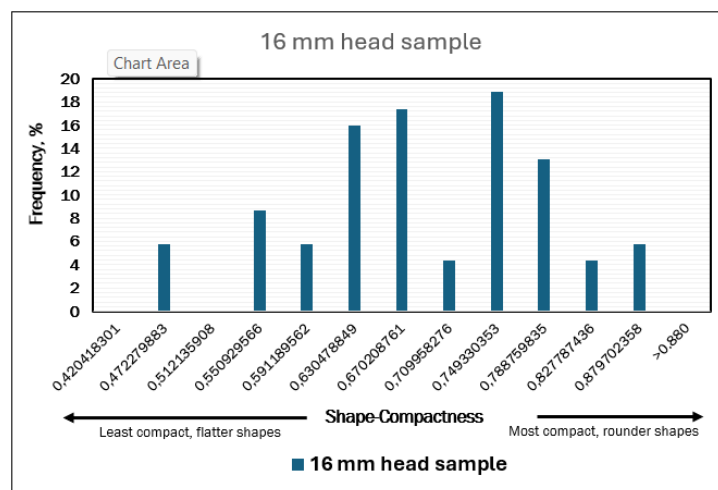
The effect of breakage mode and top size on particle shape was studied using the RhoVol. One of the advantages of using the RhoVol for densimetric analysis is its ability to measure and provide information on the ore's physical properties such as the particle shape. The RhoVol can sort particles based on three shape characteristics namely compaction, elongation and flatness (Fofana and Steyn, 2019). The compactness characteristic is mainly used in studies because precursory findings show better correlation with the volume correction factor (Fofana and Steyn, 2019).

Figure 4.13 shows the compactness distribution of the Waterberg coal samples after crushing the head sample via compressive and impact breakage to top size 3 mm. Flatter shapes are in the 0.45 to 0.49 range whereas rounder shapes are between 0.81 to 0.89 (Fofana and Steyn, 2019). As it can be seen in Figure 4.13, that the head sample is mainly composed of most compact, rounder particles. The rounder and compact particles indicate the presence of heavy dense mineral matter and the entrapment of the coal macerals within the ore particles. Initial size reduction to top size 12 mm via compressive and impact breakage shows a shift in the mass distribution of the particles from the most compact, rounder shape to mid and least compact particles. Impact breakage to top size 12 mm produced more flat, least compact particles (9% frequency) in the 0.42 to 0.51 compactness range as compared to compressive crushing (7.8% particles frequency).

Further size reduction from 12 mm to 8 mm shows an increased shift in the mass distribution from rounder to more irregular and flat particle shapes. i.e. between the mid-compact range 0.63 – 0.71, particle top size reduction to 8 mm increased the frequency of these irregular shaped particles by 2% (from 43.4% to 45.4%) for impact breakage and by 1.9% in the case of compressive breakage. This indicates that size reduction through compressive and impact breakage resulted in some liberation of the coal macerals by decreasing the volume of the particles and promoting the release of the entrapped coal mineral matter from the gangue. Impact breakage resulted in the least number (8.6% particle frequency) of most compact/rounder particles (in the 0.81 to 0.89 range) as compared to compressive crushing (10.4%) when the top size was reduced to 8 mm.

The shift in mass distribution from rounder to irregular particle shapes was also observed when the coal samples was further reduced to top size 6 mm. However, the frequency of flat material passing in the compactness range of between 0.42 - 0.551 was improved. from 6.8% to 8.1% after compressive breakage and from 7.5% to about 9.1% in the case of impact breakage. The continued shift in the mass distribution from round and irregular to flat shapes was also

observed when the particle is further reduced to top sizes 4 to 3 mm. Crushing to smaller top sizes increased the frequency percentage of flat particles and reduced the proportion of compact and irregular particles for both breakage modes. For impact breakage, crushing to top size 4 mm increased the frequency of flat particles to 11.1% and further size reduction to 3 mm improved the frequency to 13.5%. The latter was also observed after compressive breakage to top sizes 4 mm and 3 mm with an improvement from 12.2% to 15.9%. This shows that crushing to small particle size promotes the liberation of coal mineral matter from the gangue and results in clean flatter coal products of low density. As it can be seen in Figure 4.13, impact breakage resulted in more flatter and least compact coal particles in the range 0.42 – 0.512 when compared to compressive breakage up to top size 6 mm. Compressive breakage to top size 4 mm produced more least compact particles. There is insignificant difference between the two breakage modes when the top size reduced to 3 mm.



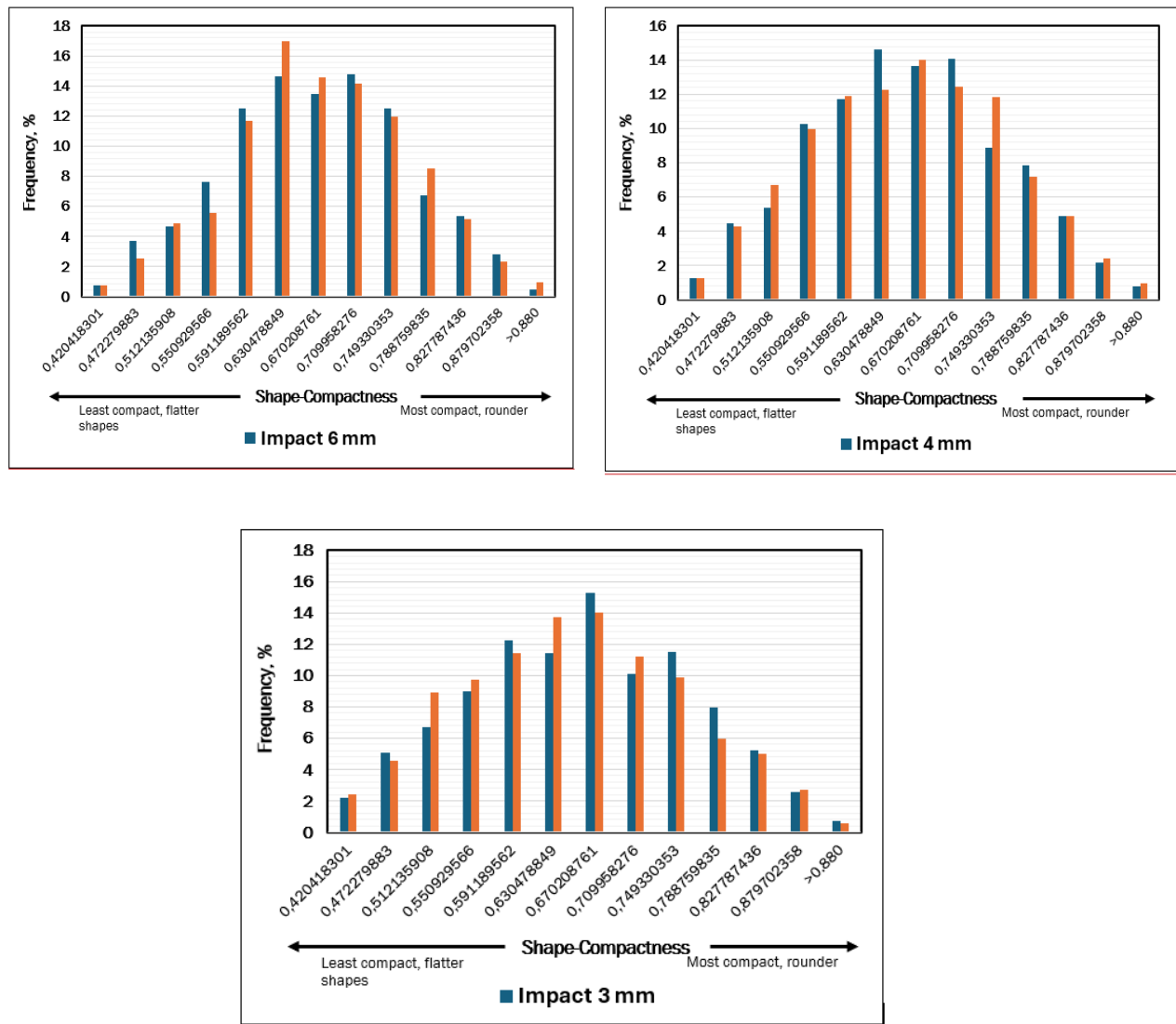


Figure 4.13: Compactness distribution of Waterberg coal particles from top size 16 mm to 3 mm after compressive and impact breakage.

The results from the test work shows that there is a correlation between the breakage mode, top size and shape and their influence the liberation of coal. As previously reported in sections 4.3.1 and 4.3.2, particle size reduction from top size 16 mm to 3 mm decreased the proportion of high density particles and increased the quantity of clean coal and middlings products. The proportion of rounder shaped particles (most compact) was reduced, and the frequency of flat and irregular particles was improved with particle top size reduction to smaller sizes.

The increase in the proportion of particles in the flat to irregular particle shape range is due to the breakage and volume reduction of the coarse, spherical (most compact) particles into smaller, irregular and flat (less compact) particles. As previously discussed in the literature (chapter 2), coarse/large particles are associated with impurities and cracks rendering them more susceptible to breakage. Sharp edges found in coarse particles also act as local sites of

stress formation and increases the particles susceptibility to breakage. The decrease in the particles frequency when the top size was reduced from 4 mm to 3mm via impact breakage may be due to particle breakage resistance at smaller sizes. The flat and/ irregular shape at smaller particle sizes makes it difficult to crush the coal via the impact dead weight.

Particle shape and size can influence breakage because of their impact on the subsequent fragments generated from breakage as shown by the wide range of shapes received from breaking particles of different sizes (Sehlabaka, 2021). Studies have shown that agglomerates with intricate surfaces can hinder breakage and behave differently in collisions than spherical particles (Zheng *et al.*, 2015). Impact breakage resulted in more flatter particles than compressive breakage up to top size 4 mm. This may be due to the breakage energy absorbed by the particles and the sphericity of the crushed particles. In the study by Gang *et al.*, (2019), it was reported that the particles shape greatly affects the impact loading mode and breakage progress. The specific breakage energy is related to the sphericity of the primary size (Gang *et al.*, 2019).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The effect of breakage mode and top size on coal liberation and yield was investigated using the RhoVol densimetric analyser. The effect of breakage mode and top size on particle shape was also investigated using data obtained from the RhoVol. Proximate analysis was done to determine the ash, CV, moisture and volatile matter content of the coal. Coal from the Waterberg coalfield at top size 16 mm was subjected to compressive and impact breakage to top sizes 12 mm, 8 mm, 6 mm, 4 mm and 3 mm. Proximate analysis show that the 16 mm head sample is of poor quality with high ash content (about 60.7%). The high ash and mineral matter necessitate the need for beneficiation of the coal. The RhoVol was used for densimetric analysis and pycnometer for true density. The volume correction needed to calibrate the RhoVol data was established from the pycnometer measurements.

Initial RhoVol densimetric analysis shows that the 16 mm head sample is mostly dominated by a high proportion of dense and middlings particles. This is mainly because coal from the Waterberg coalfield is of poor quality, and it is highly interlayered with clay and mudstones. Compressive breakage to top size 12 mm had negligible effect on the liberation of low-density clean coal (RD <1.4) products. However, a small proportion (1.7% by mass) of clean coal products was obtained after impact crushing to top size 12 mm. There was a significant increase (about 3.2% by mass) in the proportion of clean coal products when the top size was reduced to 8 mm via compression breakage. Impact breakage to top size 8 mm resulted in an increase in the proportion of clean coal products from 1.7% to 6.4% (by mass). For compressive breakage, the proportion of clean coal products was doubled when the top size was further reduced to 6 mm. Gradual improvements in the proportion of clean coal products was observed when the top sizes were further reduced to 4 mm and 3 mm for both breakage modes. After each subsequent crushing stage, there was a shift in the mass distribution of the particles from dense to the middlings and low-density clean coal products.

Coal washability curves show that compressive breakage to top size 12 mm had little effect on the mass yield of clean coal products as compared to the 5.7% low-density clean coal yield obtained after impact crushing. Compressive breakage to top size 8 mm significantly improved the mass yield of low-density clean coal products (at RD cutpoint 1.4) from 0.3% to 14.4%.

Impact breakage to top size 8 mm significantly improved the yield of low-density clean coal products from 5.7% to 18%. Compressive breakage to top size 6 mm further improved the mass yield of clean coal products to 21.6% as compared to 21.1% obtained after impact breakage. There were progressive but small improvements in the mass yield of clean coal products when the coal was crushed to top sizes 4 mm and 3 mm. Compressive and impact breakage to top size 3 mm resulted in the highest coal yield at 31.3% and 31.4% (at RD cutpoint 1.4) respectively. However, crushing to smaller top sizes (3 mm) can lead to excessive fines generation that can offset the benefits of the improved liberation.

Cumulative mass yield trend shows that the yield of the middlings products between RD interval 1.4-1.8 decreases with the reduction in the particles top size. Compared to the head sample (16 mm), impact breakage to top size reduction to 3 mm decreased the middlings fraction from 60-45%. The mass yield of the middlings products was reduced from 60-50%. Compressive breakage of the 16 mm head sample to 3 mm decreased the mass yield of high-density coal products decreased from 40-18% as compared to 40-20% yield obtained after impact breakage.

Crushing to smaller sizes liberated more of the lower density clean coal material and improved their mass yield. Crushing 8 mm, 6 mm, 4 mm and 3 mm yielded approximately 25-35% of the low-density clean coal products as compared to 5% attained after impact breakage to 12 mm. Assuming a density cutpoint of 1.4, impact breakage resulted in the highest coal mass yields at top sizes 12 mm, 8 mm and 4 mm. There are negligible differences in the mass yield of compressive and impact crushed coal at top size 6 mm and 3 mm. Significant low-density clean coal yields were reported when the coal was crushed to between 8 mm and 6 mm. To maximize the recovery of low-density clean coal without necessarily generating excessive fines, coal from the Waterberg coalfield should ideally be crushed to between 8- and 6-mm. Nevertheless, the optimal size would also be dependent on the plant economics, cost associated with fines handling and downstream processing.

As particle top size decreases (6 mm, 4 mm, 3 mm), the difference between compressive and impact crushing is reduced, indicating that the crushing method has less influence on clean coal yield at finer sizes. Coarse particles are susceptible to breakage due to the presence of large cracks and impurities associated with the ore. At small particle sizes, Waterberg coal is resistant to breakage and tend to undergo plastic deformation when crushed necessitating the need of repetitive applied forces. These findings highlight how important top size and breaking mode are to maximizing yield during coal beneficiation.

Results on the effect of breakage mode and top size on particle shape show that the head sample was mainly composed of rounder and more compact particles. Size reduction to 12 and 8 mm shows an increasing shift from more spherical to irregular shaped particles. Impact breakage to top size 12 mm produced more flat, least compact particles (9% frequency) in the 0.42 to 0.51 compactness range as compared to compressive crushing (7.8% particles frequency). Further size reduction to 6 mm increased the proportion of flat particles from 6.8% to 8.1% for compressive breakage and from 7.5% to 9.1% in the case of impact breakage. Crushing to smaller sizes of 4 and 3 mm decreased the proportion of rounder and more compact and irregular shaped particles. The increase in the proportion of particles in the flat to irregular particle shape range is due to the breakage and volume reduction of the coarse, round (most compact) particles into smaller, irregular and flat (less compact) particles

The above findings show that when properly calibrated with pycnometer data, the RhoVol densimetric analyser measurements can be used for rapid densimetric analysis on coal of different sizes and shape. The RhoVol provides a non-destructive densimetric determination method that allows for the reuse of the same samples for other tests reducing the error margins associated with using different test specimens. Unlike traditional float and sink analysis that are laborious and uses hazardous chemicals, the RhoVol provides rapid and dependable densimetric data that can be employed in quick decision-making scenarios for process improvement.

5.2. Recommendations

- The head sample was prepared and crushed using a jaw crusher which may have resulted in some form of liberation. It is recommended that in sample preparation, the head samples be crushed via compressive and impact breakage.
- For improved yield results in case of compressive breakage, it is recommended that the direction of the applied force relative to the bedding be changed. The study by Viljoen *et al.*, (2015) shows that the direction of the applied load greatly influenced the expansion of existing cracks and the dissemination of newly formed cracks

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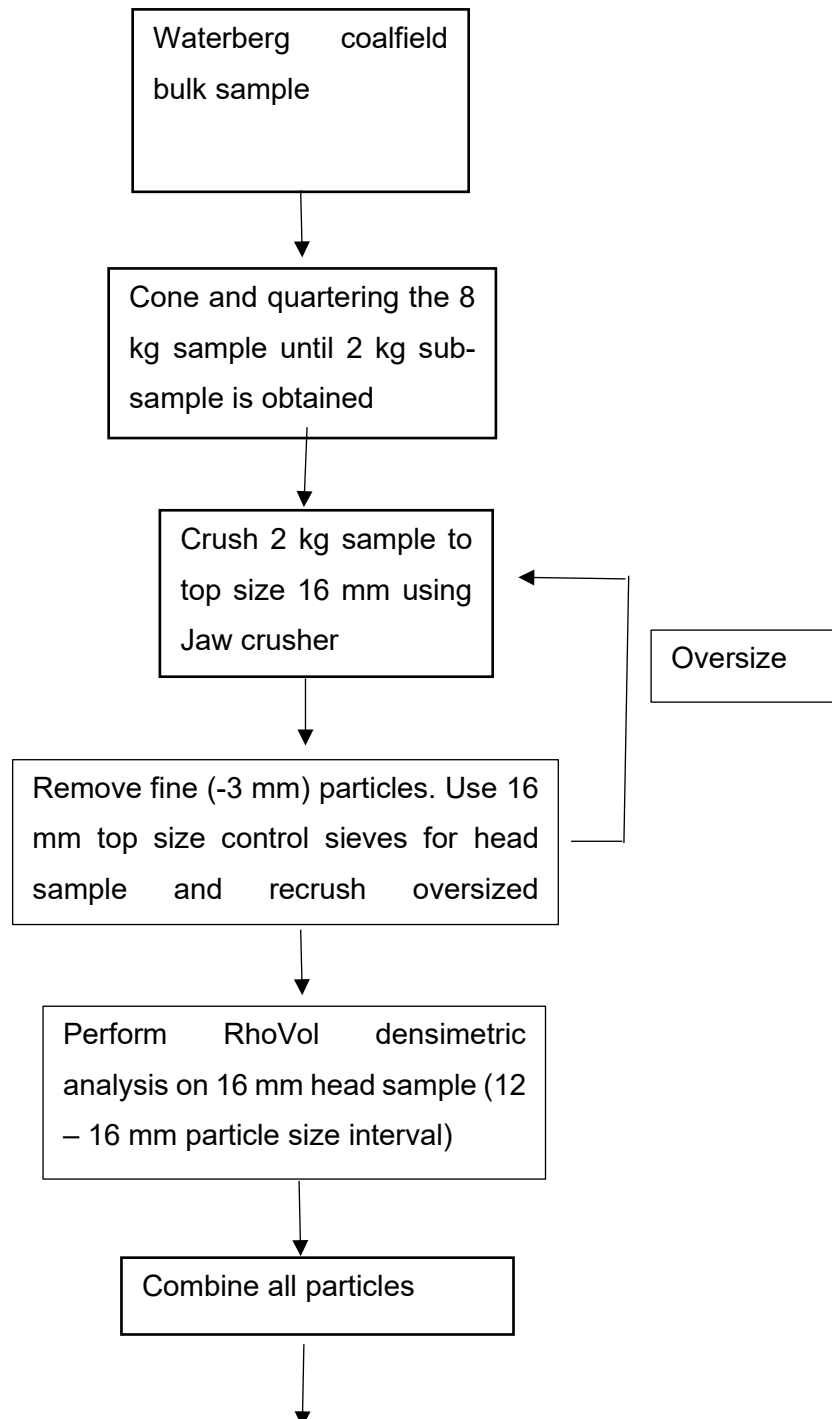
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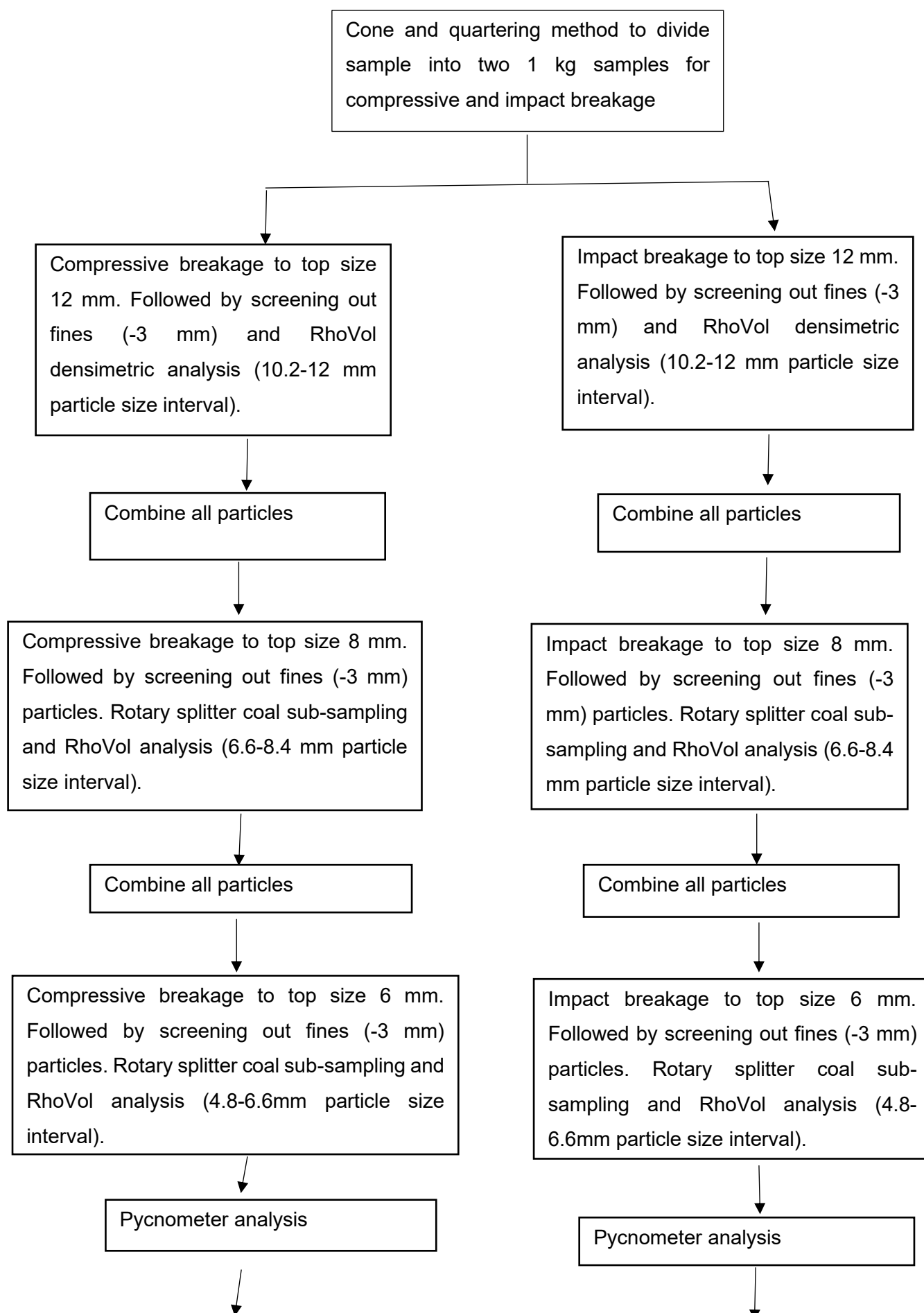
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ANNEXURE A

Annexure A contains additional notes regarding the experimental procedure used within the study.

A.1 Experimental procedure





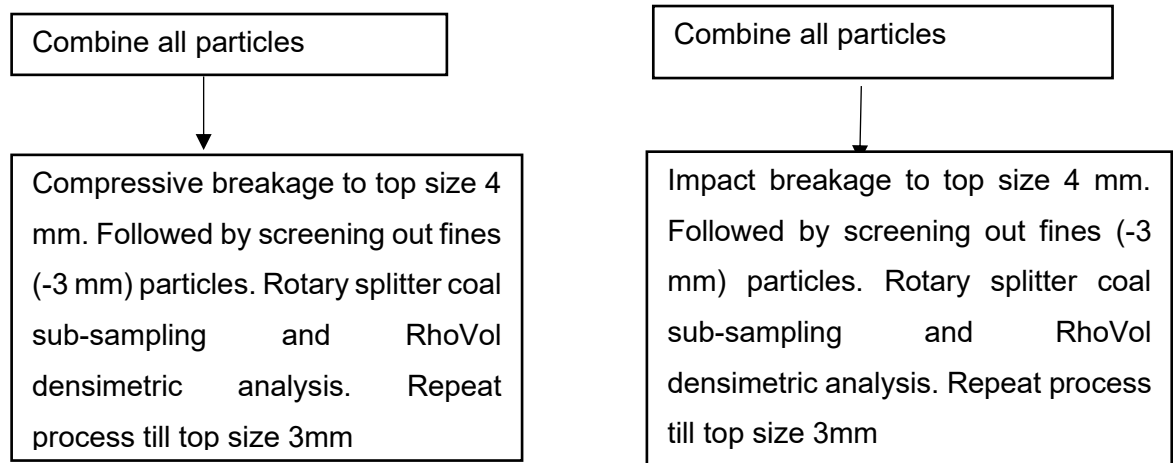


Figure 6.1: Experimental procedure

ANNEXURE B

RESULTS AND DISCUSSION – ADDITIONAL CONTENT

Annexure B contains additional content with regards to the experimental results found within the study.

B.1. Proximate and ultimate analysis report

Table 7.1: Proximate and ultimate analysis report

North West University
For Attention: Rene Bekker
Email: rene.bekker@nwu.ac.za

Ref Nr	2324-1167
Date Received	05/10/2023
Reported by	Willem Swanepoel
Status	FINAL
Report Date	30/10/2023
Date Analysed	Oct-23
	-

308 Barolong Street
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Sunderland Ridge X10
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Fax: +27(0)86 631 4743



Bureau Veritas Testing and
Inspections South Africa
Sunderland Ridge
Reg N° 2002/003217/07



CERTIFICATE OF ANALYSIS

Sample Identification	% Inherent moisture content	% Ash content	% Ash content	% Volatile Matter	% Volatile Matter	% Fixed carbon (by calculation)	Gross Calorific Value (MJ/kg)
Mass (g)	(air-dried)	(air-dried)	(dry basis)	(air-dried)	(dry basis)	(air-dried)	(air-dried)
DISCARD 3mm 6mm HEIGHT 20Hz BIN 3	2.65	20.30	20.85	32.05	32.92	44.90	25.73
2 DISCARD 3mm 6mm HEIGHT 20Hz BIN 4	2.15	34.00	34.75	26.95	27.54	36.80	20.66
3 DISCARD 3mm 6mm HEIGHT 20Hz BIN 5	1.40	65.60	66.53	15.70	15.92	17.30	8.20
4 PRODUCT 4mm 7mm HEIGHT 30Hz BIN 3	2.60	17.45	17.92	33.70	34.60	46.20	26.85
5 PRODUCT 4mm 7mm HEIGHT 30Hz BIN 5	1.45	62.80	63.72	16.65	16.89	19.00	8.77
6 PRODUCT 4mm 7mm HEIGHT 30Hz BIN 7	1.10	84.90	85.84	9.40	9.50	4.60	2.00
7 DISCARD 3mm 5mm HEIGHT 30Hz BIN 3	2.50	21.95	22.51	31.80	32.62	43.70	25.16
8 DISCARD 3mm 5mm HEIGHT 30Hz BIN 5	1.45	65.35	66.31	15.15	15.37	17.90	7.73
9 DISCARD 3mm 5mm HEIGHT 30Hz BIN 6	1.20	78.85	79.81	11.30	11.44	8.60	3.83
10 PRODUCT 3mm 5mm HEIGHT 30Hz BIN 3	2.45	22.10	22.66	31.35	32.14	44.00	25.10
11 PRODUCT 3mm 5mm HEIGHT 30Hz BIN 5	1.55	62.40	63.58	16.25	16.51	19.70	8.59
12 PRODUCT 3mm 5mm HEIGHT 30Hz BIN 7	1.10	81.80	82.71	10.90	11.02	6.20	2.74
PRODUCT 4mm 5mm HEIGHT 25Hz BIN 3	2.55	18.40	18.88	32.85	33.71	46.10	26.40
PRODUCT 4mm 5mm HEIGHT 25Hz BIN 4	2.10	39.25	40.09	24.60	25.13	34.00	18.65
PRODUCT 4mm 5mm HEIGHT 25Hz BIN 5	1.65	59.00	59.99	17.05	17.34	22.20	10.85
DISCARD 4mm 7mm HEIGHT 30Hz BIN 2	1.60	60.30	61.28	18.00	18.29	20.10	10.03
DISCARD 4mm 7mm HEIGHT 30Hz BIN 5	1.60	60.20	61.18	16.90	17.17	21.30	Insufficient mass
DISCARD 4mm 7mm HEIGHT 30Hz BIN 6	1.50	70.00	71.07	13.90	14.11	14.60	7.12
DISCARD 3mm 7mm HEIGHT 25Hz BIN 3	2.70	20.30	20.86	32.20	33.09	44.80	25.84
DISCARD 3mm 7mm HEIGHT 25Hz BIN 7	1.20	82.45	83.45	10.20	10.32	6.10	2.80
PRODUCT 3mm 6mm HEIGHT 20Hz BIN 3	2.65	19.15	19.67	32.85	33.74	45.20	26.24
PRODUCT 3mm 6mm HEIGHT 20Hz BIN 4	2.05	40.20	41.04	24.15	24.66	33.50	18.36
PRODUCT 3mm 6mm HEIGHT 20Hz BIN 5	1.55	59.70	60.64	16.95	17.22	21.70	10.04
DISCARD 4mm 5mm HEIGHT 25Hz BIN 3	2.65	21.15	21.73	31.65	32.51	44.40	25.54
DISCARD 4mm 5mm HEIGHT 25Hz BIN 5	1.65	61.50	62.53	16.15	16.42	20.60	9.50
DISCARD 4mm 5mm HEIGHT 25Hz BIN 7	1.25	81.00	82.03	10.65	10.78	7.00	3.36
PRODUCT 3mm 7mm HEIGHT 25Hz BIN 3	2.70	18.70	19.22	33.30	34.22	45.30	26.28
PRODUCT 3mm 7mm HEIGHT 25Hz BIN 4	2.15	37.30	38.12	24.55	25.09	35.90	19.42
PRODUCT 3mm 7mm HEIGHT 25Hz BIN 5	1.50	60.35	61.27	16.90	17.16	21.20	10.22

These samples were analysed using coal standard methods

Due to low sample mass received, duplicate or repeat analyses might not have been possible.

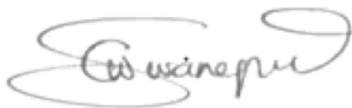
Description	Procedure / Test Method
Sample preparation	BV-TPM-001 based on ISO 13909-4: 2001
Moisture content (%)	BV-TPM-010 based on ISO 11722: 1999
Ash content (%)	BV-TPM-011 based on ISO 1171: 2010

Volatile matter content (%) BV-TPM-012 based on ISO 562: 2010
 Total sulphur (%) BV-TPM-013 based on ISO 19579: 2006
 Ultimate analysis Based on ISO 12902 - CHN Instrumental method (Subcontracted Test)

Results marked "Not SANAS Accredited" in this report are not included in the SANAS Schedule of Accreditation for this laboratory.

Results marked "Subcontracted Test" in this report are not included in the SANAS Schedule of Accreditation for this laboratory.

Results reported are only representative of the sample received for testing. Sample preparation will deviate from ISO13909-4: 2001(E) Table 1 (Minimum Mass of Samples After Division) where insufficient material was supplied or generated due to the nature of the requirements. While every endeavour has been made to ensure that the results reported are accurate, Bureau Veritas Testing and Inspections South Africa shall not be liable for any error nor for any damage or loss whatsoever that may arise from the issuing of this certificate. This certificate may not be reproduced in part or full without written permission from the Technical Managers of Bureau Veritas Testing and Inspections South Africa. Please note that samples will be discarded three months after date of Final Report unless instructed otherwise by client.



C.W. Swanepoel
Technical Signatory

BV TISA

2324-1167

Page 1 of 1



North West University

School of Chemical and Minerals Engineering

Final Report Proximate Analysis

Worksheet
Sample Date

Elijah Moletsane
08-Jul-24

Sample	% Moisture	% Volatile	% Ash	% Fixed Carbon
Bin 1 (Compression) +4mm	0,00	32,63	20,89	46,48
	0,00	33,49	18,90	47,61
Average	0,00	33,06	19,90	47,05
Standard Deviation	0,00	0,61	1,41	0,80
Bin 2 (Compression) +4mm	0,00	31,11	29,76	39,13
	0,00	30,28	29,66	40,06
	0,00	27,80	29,16	43,04
Average	0,00	29,73	29,53	40,74
Standard Deviation	0,00	1,72	0,32	2,04
Bin 3 (Compression) +4mm	0,00	27,80	34,90	37,30
	0,16	28,44	34,75	36,64
	0,20	27,61	35,07	37,13

Average	0,12	27,95	34,91	37,02
Standard Deviation	0,11	0,44	0,16	0,34
Bin 4 (Compression) +4mm	0,00	25,58	41,33	33,08
	0,34	25,14	41,85	32,66
	0,03	25,39	41,51	33,08
Average	0,12	25,37	41,56	32,94
Standard Deviation	0,19	0,22	0,26	0,24
Bin 5 (Compression) +4mm	0,00	24,65	39,54	35,80
	0,16	23,68	40,32	35,84
	0,07	23,06	40,49	36,38
Average	0,08	23,80	40,12	36,01
Standard Deviation	0,08	0,80	0,51	0,32
Bin 6 (Compression) +4mm	0,22	16,17	64,11	19,50
	0,30	15,82	64,37	19,52
	0,18	18,16	63,33	18,34
Average	0,23	16,72	63,93	19,12
Standard Deviation	0,06	1,26	0,54	0,68
Bin 7 (Compression) +4mm	0,98	14,45	74,11	10,46
	1,36	15,63	73,58	9,43
	1,12	15,37	74,03	9,48
Average	1,15	15,15	73,90	9,79
Standard Deviation	0,19	0,62	0,29	0,58
Bin 8 (Compression) +4mm	0,76	12,42	75,45	11,37
	0,70	13,19	75,41	10,70
	0,65	12,29	75,61	11,45
Average	0,70	12,63	75,49	11,17
Standard Deviation	0,06	0,48	0,11	0,41
Bin 9 (Compression) +4mm	0,72	13,41	78,23	7,63
	0,54	13,69	77,87	7,90
	0,53	12,95	78,01	8,51
Average	0,60	13,35	78,04	8,01
Standard Deviation	0,11	0,37	0,19	0,45
Bin 10 (Compression) +4mm	1,04	11,05	86,04	1,87
	0,81	12,88	83,07	3,24
	1,25	14,27	81,59	2,89
Average	1,03	12,74	83,57	2,67
Standard Deviation	0,22	1,62	2,27	0,71
Bin 1 (Impact) +3mm	0,59	49,25	12,24	37,91
Insufficient sample for triplicate				
"Only 0.0337g sample available"				
Average	0,59	49,25	12,24	37,91
Bin 2 (Impact) +3mm	1,04	31,87	23,54	43,55
	0,69	33,20	24,17	41,94
	0,79	33,27	20,69	45,25

Average	0,84	32,78	22,80	43,58
Standard Deviation	0,18	0,79	1,86	1,66
Bin 3 (Impact) +3mm	0,75	22,57	38,87	37,81
Only sufficient for duplicate	1,06	24,21	38,82	35,91
Average	0,91	23,39	38,85	36,86
Standard Deviation	0,22	1,16	0,04	1,35
Bin 4 (Impact) +3mm	0,86	21,81	40,09	37,23
	0,84	21,81	40,42	36,93
	0,71	21,98	40,32	36,99
Average	0,80	21,87	40,28	37,05
Standard Deviation	0,08	0,10	0,17	0,16
Bin 5 (Impact) +3mm	1,99	20,92	49,59	27,50
	1,49	20,61	49,71	28,18
	1,74	22,62	49,15	26,49
Average	1,74	21,39	49,49	27,39
Standard Deviation	0,25	1,08	0,30	0,85
Bin 6 (Impact) +3mm	0,66	15,62	59,75	23,98
Only sufficient for duplicate	0,47	16,72	59,55	23,26
Average	0,57	16,17	59,65	23,62
Standard Deviation	0,13	0,78	0,14	0,51
Bin 7 (Impact) +3mm	0,84	13,68	70,50	14,98
Only sufficient for duplicate	0,92	14,20	72,60	12,29
Average	0,88	13,94	71,55	13,63
Standard Deviation	0,06	0,36	1,48	1,90
Bin 8 (Impact) +3mm	0,70	13,08	73,59	12,63
	0,45	13,95	73,46	12,14
	0,64	14,45	73,40	11,51
Average	0,60	13,82	73,48	12,09
Standard Deviation	0,13	0,69	0,09	0,56
Bin 9 (Impact) +3mm	0,70	11,80	77,56	9,93
	1,02	12,78	77,39	8,82
	0,72	11,94	77,76	9,58
Average	0,81	12,17	77,57	9,44
Standard Deviation	0,18	0,53	0,19	0,57
Bin 10 (Impact) +3mm	0,65	11,56	84,17	3,63
	0,79	11,85	83,80	3,55
	0,73	13,75	83,90	1,62
Average	0,72	12,39	83,96	2,93
Standard Deviation	0,07	1,19	0,19	1,14

B.2. RhoVol data

Due to RhoVol machine availability and time constraints during the time of this study, a rotary splitter was used for sampling purposes and sub-samples were used for densimetric analysis. Tables 7.2-7.12 shows the washability data of compressive and impact breakage crushed coal sample at different top sizes.

Table 7.2: 16 mm head sample coal washability data

Density intervals	Average	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
1,1-1,2	1,15	0	0	0	0
1,2-1,3	1,25	0	0	0	0
1,3-1,4	1,35	0	0	0	0
1,4-1,5	1,45	0	0	0	0
1,5-1,6	1,55	0	0	0	0
1,6-1,7	1,65	5672,2	5672,2	8,56	8,56
1,7-1,8	1,75	14281,2	19953,4	30,12	21,56
1,8-1,9	1,85	20830	40783,4	61,56	31,44
1,9-2	1,95	25469,3	66252,7	100,00	38,44
Sum		66252,7			

Table 7.3: Compressive breakage 12 mm coal washability data

Density intervals	Average	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
1,1-1,2	1,15	16,3	16,3	0,01	0,01
1,2-1,3	1,25	45,2	61,5	0,05	0,04
1,3-1,4	1,35	0	61,5	0,05	0
1,4-1,5	1,45	274,2	335,7	0,29	0,24
1,5-1,6	1,55	5430	5765,7	4,95	4,66
1,6-1,7	1,65	13751,3	19517	16,74	11,80
1,7-1,8	1,75	31966,2	51483,2	44,17	27,42
1,8-1,9	1,85	38837,7	90320,9	77,48	33,32
1,9-2	1,95	26247,3	116568,2	100	22,52
Sum		116568,2			

Table 7.4: Compressive breakage 8 mm coal washability data

Density intervals	Average	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
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1,1-1,2	1,15	17,5	17,5	0,01	0,01
1,2-1,3	1,25	478,7	496,2	0,39	0,38
1,3-1,4	1,35	3491,2	3987,4	3,15	2,76
1,4-1,5	1,45	14267	18254,4	14,44	11,29
1,5-1,6	1,55	22406	40660,4	32,17	17,73
1,6-1,7	1,65	26927,7	67588,1	53,47	21,30
1,7-1,8	1,75	26167,1	93755,2	74,18	20,70
1,8-1,9	1,85	16558,6	110313,8	87,28	13,10
1,9-2	1,95	16079,4	126393,2	100,00	12,72
Sum		126393,2			

Table 7.5: Compressive breakage 6 mm coal washability data

Density intervals	Average	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
1,1-1,2	1,15	811,2	811,2	0,63	0,63
1,2-1,3	1,25	1775	2586,2	1,99	1,37
1,3-1,4	1,35	7212,6	9798,8	7,55	5,56
1,4-1,5	1,45	18233,2	28032	21,61	14,06
1,5-1,6	1,55	28338,2	56370,2	43,45	21,85
1,6-1,7	1,65	18183,9	74554,1	57,47	14,02
1,7-1,8	1,75	19409,1	93963,2	72,43	14,96
1,8-1,9	1,85	16884,5	110847,7	85,45	13,02
1,9-2	1,95	18874,6	129722,3	100,00	14,55
Sum		129722,3			

Table 7.6: Compressive breakage 4 mm coal washability data

Density intervals	Average	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
1,1-1,2	1,15	601,4	601,4	0,82	0,82
1,2-1,3	1,25	1059,3	1660,7	2,27	1,45
1,3-1,4	1,35	5000,2	6660,9	9,11	6,84
1,4-1,5	1,45	10408,3	17069,2	23,35	14,24
1,5-1,6	1,55	11911	28980,2	39,64	16,29
1,6-1,7	1,65	11502	40482,2	55,37	15,73
1,7-1,8	1,75	9621,2	50103,4	68,53	13,16
1,8-1,9	1,85	12364,1	62467,5	85,45	16,91
1,9-2	1,95	10639,9	73107,4	100,00	14,55

Sum		73107,4			
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Table 7.7: Compressive breakage 3 mm coal washability data

Density intervals	Average	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
1,1-1,2	1,15	441,7	441,7	1,59	1,59
1,2-1,3	1,25	1400,3	1842	6,63	5,04
1,3-1,4	1,35	2972,7	4814,7	17,32	10,69
1,4-1,5	1,45	3877,6	8692,3	31,27	13,95
1,5-1,6	1,55	4686,8	13379,1	48,13	16,86
1,6-1,7	1,65	3585,8	16964,9	61,02	12,90
1,7-1,8	1,75	4035,6	21000,5	75,54	14,52
1,8-1,9	1,85	3512	24512,5	88,17	12,63
1,9-2	1,95	3288,1	27800,6	100,00	11,83
Sum		27800,6			

Table 7.8: Impact breakage 12 mm coal washability data

Density intervals	Average Density	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
1,1-1,2	1,15	0	0	0,00	0,00
1,2-1,3	1,25	357,3	357,3	0,32	0,32
1,3-1,4	1,35	1581,9	1939,2	1,71	1,39
1,4-1,5	1,45	4525	6464,2	5,70	3,99
1,5-1,6	1,55	6857,1	13321,3	11,74	6,05
1,6-1,7	1,65	15687,9	29009,2	25,58	13,83
1,7-1,8	1,75	38665,1	67674,3	59,66	34,09
1,8-1,9	1,85	23169,8	90844,1	80,09	20,43
1,9-2	1,95	22583,5	113427,6	100,00	19,91
Sum		113427,6			

Table 7.9: Impact breakage 8 mm coal washability data

Density intervals	Average	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
1,1-1,2	1,15	340,7	340,7	0,26	0,26
1,2-1,3	1,25	1781,7	2122,4	1,60	1,34

1,3-1,4	1,35	6280	8402,4	6,34	4,74
1,4-1,5	1,45	15396,4	23798,8	17,96	11,62
1,5-1,6	1,55	22320	46118,8	34,81	16,85
1,6-1,7	1,65	20531,7	66650,5	50,31	15,50
1,7-1,8	1,75	14798,6	81449,1	61,48	11,17
1,8-1,9	1,85	26179,3	107628,4	81,24	19,76
1,9-2	1,95	24857,1	132485,5	100,00	18,76
Sum		132485,5			

Table 7.10: Impact breakage 6 mm coal washability data

Density intervals	Average	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
1,1-1,2	1,15	234,1	234,1	0,17	0,17
1,2-1,3	1,25	1893,6	2127,7	1,58	1,41
1,3-1,4	1,35	8109,5	10237,2	7,62	6,04
1,4-1,5	1,45	18061,5	28298,7	21,07	13,45
1,5-1,6	1,55	24968,5	53267,2	39,67	18,59
1,6-1,7	1,65	20648,8	73916	55,04	15,38
1,7-1,8	1,75	24921,1	98837,1	73,60	18,56
1,8-1,9	1,85	17534,1	116371,2	86,66	13,06
1,9-2	1,95	17916,8	134288	100,00	13,34
Sum		134288			

Table 7.11: Impact breakage 4 mm coal washability data

Density intervals	Average	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
1,1-1,2	1,15	388,6	388,6	0,54	0,54
1,2-1,3	1,25	2044,7	2433,3	3,38	2,84
1,3-1,4	1,35	4296,5	6729,8	9,36	5,98
1,4-1,5	1,45	11112,3	17842,1	24,82	15,46
1,5-1,6	1,55	13504,9	31347	43,60	18,79
1,6-1,7	1,65	10056,3	41403,3	57,59	13,99
1,7-1,8	1,75	11726,7	53130	73,90	16,31
1,8-1,9	1,85	9866,2	62996,2	87,63	13,72
1,9-2	1,95	8893,7	71889,9	100,00	12,37
Sum		71889,9			

Table 7.12: Impact breakage 3 mm coal washability data

Density intervals	Average	Fractional mass (mg)	Mass cumulative	Cumulative %	Mass distribution %
1,1-1,2	1,15	295,3	295,3	1,04	1,04
1,2-1,3	1,25	1108,2	1403,5	4,96	3,91
1,3-1,4	1,35	2949,3	4352,8	15,37	10,42
1,4-1,5	1,45	4541	8893,8	31,41	16,04
1,5-1,6	1,55	4816,8	13710,6	48,42	17,01
1,6-1,7	1,65	3971,6	17682,2	62,45	14,03
1,7-1,8	1,75	3524,8	21207	74,90	12,45
1,8-1,9	1,85	3765,2	24972,2	88,20	13,30
1,9-2	1,95	3342,5	28314,7	100,00	11,80
Sum		28314,7			

C.1. Honor Pledge Form



Faculty of Engineering (F-ENG)

Assessment submission declaration

Student name: Phasomane Elija Moletsane

Student number: 47129867

Date: 2025/07/21

Module code: I801P

Lecture: Prof. Q.P. Campbell & Prof. M. Le Roux

Assessment nr: Dissertation

Declaration:

I, the above named student, declare the following:

1. This assessment submitted is my own work and no unlawful help was obtained during the execution of this work.
2. I understand what plagiarism is, as defined in the study guide of the module, and that plagiarism is wrong.
3. I have not shared my work with anyone and have not and will not allow anyone to copy my work with the intention of passing it off as his/her own work.
4. I acknowledge that I am aware of the content of the Faculty of Engineering Honour Code document and the subsequent sanctions proposed for academic dishonesty.

P.E. Moletsane

2025/07/21

Signature

Date

Faheed – interesting comments on tariffs war etc

<https://www.youtube.com/watch?v=qE3V0sEre2U>

Maddows – authoritarian looks like?

<https://www.youtube.com/shorts/rVkosH7CDy4>

