Measuring the effect of breakage mode and top size on coal liberation using the RhoVol densimetric analysis machine

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Abstract. Coal from the Waterberg coalfield is associated with high mineral that necessitates the need for beneficiation to improve the grade. Comminution is usually employed for ore processing and the liberation of valuable coal macerals from the gangue. In this study, the effect of breakage mode and top size on coal liberation was investigated using the RhoVol densimetric analyser. RhoVol densimetric analysis show that subjecting the 16 mm feed sample to either compressive or impact breakage to top size 12 mm had little effect on the liberation of clean coal products of RD <1.4. Size reduction to top size 8 mm significantly increased the mass yield of clean coal products to 14.4% for compressive breakage and 17.9% in the case of impact breakage. A substantial increase in the mass yield of clean coal products was also observed when the top size was reduced to 6 mm for both breakage modes. Particle breakage to top size below 6 mm, i.e. to top size 4 mm had no significant effect on the mass yield of clean coal products for both breakage mechanisms. For both breakage mechanisms, top size reduction decreased the number of near-dense particles while the quantity of liberated middlings and clean coal products increased. PSD analysis show that impact breakage was more effective in the reduction of coarser agglomerates to finer particles as compared to compressive breakage. Compared to compressive breakage, impact breakage was more effective in the liberation of the coal and improved the mass yield of clean coal products.

1 Introduction

South Africa's primary energy source, coal, contributes 80% of the country's electricity and 35.6% of the world's supply [1]. Coal from the Waterberg coalfield is seen as a potential replacement for depleting Mpumalanga province coalfield resources [2-4]. However, this coal is of low quality and is associated with high ash and high volatile matter that necessitates the need for beneficiation to improve the coal grade [5-7]. Comminution techniques are usually employed to reduce ore sizes and to liberate the valuable minerals from the unwanted

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gangue matter [8]. Commonly used methods for size reduction and coal liberation includes compressive and impact breakage.

Various studies have been previously conducted to investigate the effect of compressive and impact breakage mechanisms [9-10]. In the case of impact breakage, coal breakage is influenced by the input energy, quantity of particles subjected to crushing and the impact surface [10-12]. For compressive breakage, the change in input energy and quantity of particles (single or multi-layer setting) affect the breakage of particles [10]. Particles physical properties such as the size, shape, friability and hardness also have an effect on the breakage of coal [13-16]. Other studies have shown the influence of chemical properties on coal breakage [17-18]. According to Fu and Zeng [19] the presence of minerals increased the coal's maximum strength, elastic modulus, and residual strength in uniaxial conditions.

The liberation of coal macerals from the gangue and sizing of the coal products should be carefully controlled as to prevent excessive generation of fines [20]. Fines are difficult to handle, require complex wet processing and dewatering treatment and may render processes uneconomical [11, 21, 22].

To determine the optimal top size for liberation and further retreatment, densimetric analysis techniques are employed. In this study, the RhoVol densimetric analyser was used to generate densimetric data to measure the effect of breakage mode and top size on coal liberation. **Error! Reference source not found.** shows the RhoVol densimetric analysis machine used in this study.

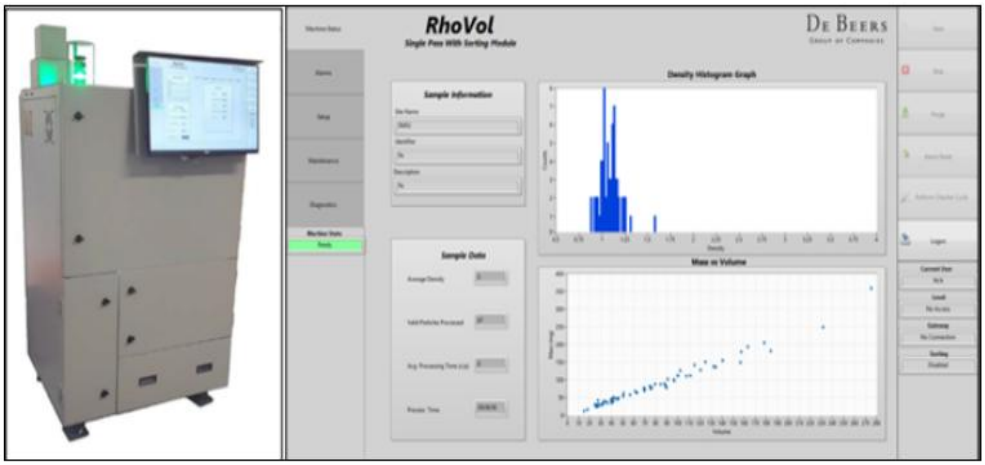


Fig. 1. RhoVol densimetric analysis machine (De Beers Ignite).

The RhoVol is a densimetric device that weighs and measures the volumes of individual particles utilizing a fast mass weighing compartment to measure particle density and a series of cameras positioned at various angles to determine the volume [23]. The cameras record and generate real-time three-dimensional reconstructed images of individual particles and provides additional data such as particle size, shape, and morphology [23-24]. Additionally, the RhoVol has a sorting module that allows the user to pre-determine the fractions of ore particles that are sorted into any of the various parameters. 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 are time consuming [25-26]. Botlhoko [25] 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 [25].

In this study, the effect of compressive and impact breakage at different top sizes on coal liberation is investigated. The objective is to determine which breakage mode, and top size produced the highest clean coal yields using the RhoVol.

2 Experimental procedure

Lump coal from the Waterberg coalfield was crushed to top size 16 mm using a laboratory jaw crusher. 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 was then divided into a sample of about 2 kg by applying the cone and quartering technique (SANS 18283:2007/ISO 18283: 2006). Densimetric analysis using the RhoVol densimetric analyser was done on the 16 mm coal sample to determine the size-by-density properties of the coal particles. The coal was then divided into 2 sub-samples with a mass of about 1 kg each using the cone and quartering method in accordance with SANS 18283:2007/ISO 18283: 2006. 1† kg sample was used for compressive breakage testwork while the other sample was used for impact crushing test. An 80 kg rudimentary lawn roller as shown in **Error! Reference source not found.** was used for compressive breakage of the particles. Rectangular steel plates of width of 0.5 m and length of 2 m flat were fitted with flat bars of varying sizes (16, 12, 8, 6, 4 and 3 mm) on the sides to determine the different top sizes for compressive breakage of the particles. The lawn roller was rolled over the particles at a determined top size and hence the coal was subjected to compressive breakage.

A drop weight impact rig as shown in **Error! Reference source not found.** was used for impact breakage of the coal particles. Steel rings of 10 mm diameter with varying thickness/height (16, 12, 8, 6, 4 and 3 mm) were used to stop the dead weight at different size intervals. For impact breakage, a 14 kg dead weight was released from a height of 0.9 m onto the particles to a pre-determined top size. For both breakage mechanisms, the samples were subjected to either compressive and impact breakage at top sizes 12 mm, 8 mm, 6 mm, 4 mm and 3 mm. Compression breakage occurs when a particle is subjected to a compressive force between two surfaces causing cracking and breakage of the particle (Sehlabaka, 2021). Impact breakage refers to the instantaneous fracture or disintegration of particles by loads due to high impact stresses. Because of the non-destructive nature of the RhoVol process, the same samples could be used to crush to the next finer top since, ensuring sample consistency.

Large particles were analysed using Debtech coarse particles RhoVol machine capable of processing particles in the size range −25 mm to +8 mm, while small particles were processed using the RhoVol machine at NWU (on loan from Debtech) capable of analysing −8 mm to + 3 mm particles. After densimetric analysis of the 16 mm top size sample, the divided samples were subjected to compressive and impact breakage to top size 12 mm. Labotec ® stainless steel sieves were used for particle top size determination. The crushed 12 mm samples were then subjected to RhoVol densimetric analysis. The process was repeated by crushing the samples to different top sizes followed by RhoVol densimetric analysis up to top size 3 mm. A Micrometrics ® AccuPyc II 1340 helium gas pycnometer was used to determine the true density of the measured and sorted RhoVol particles and to calibrate the RhoVol data. It is worth noting that the coarse RhoVol machine at Debtech is not equipped with particles sorting capabilities and as such, true density analysis using the helium gas

† A sample mass of 1 kg was utilized in this investigation due to the limited availability of coal samples at that time

pycnometer was only done on sorted 6 mm, 4 mm and 3 mm particles. It was assumed that properties of the coal were independent of the particle size and a constant correction factor was applied to the coarse top sizes. Proximate analysis was done on the coal to determine the ash, moisture, fixed carbon and volatile matter content. The data obtained was used to generate densimetric and washability curves.

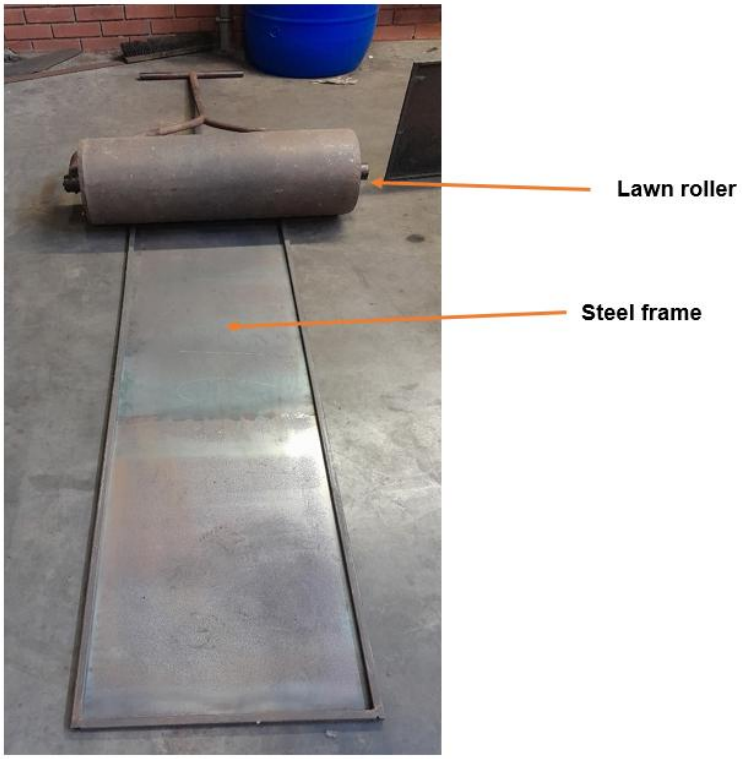


Fig. 2. Compressive breakage apparatus used for sample crushing.

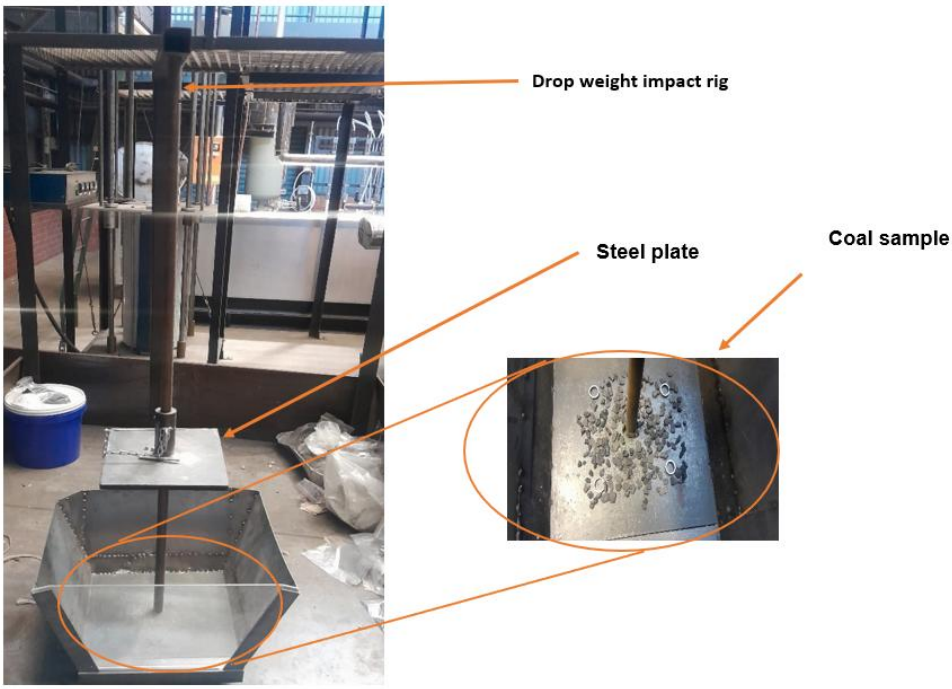


Fig. 3. Impact breakage apparatus used for sample crushing.

3 Results and discussion

3.1 Proximate analysis

The received sample's proximate analysis results are displayed in ***Error! Reference source not found.***, and show that the head sample's high ash content (above 60%) is in line with previous findings in the literature [2], indicating that the coal from the Waterberg coalfields is of poor quality.

Table 1. Proximate analysis of the head sample (ad basis).

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

3.2 Density correction factor

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 to subject them to helium pycnometry to establish their true density. The calibration of the raw RhoVol densimetric data is necessary since the 3D image densimetric analysis technique cannot precisely ascertain the true volume of porous ores. Botlhoko [25] provides detailed

procedure and discussions on the calibration of RhoVol data using gas pycnometer. **Error! Reference source not found.** shows the correlation between the bulk RhoVol density of particles and the true density measurements as determined by the helium gas pycnometer. Linear regression was used to determine the correction factor, and the obtained linear function was applied to the RhoVol generated data for post-calibration. The correction equation was determined as follows:

$$\rho\_Corrected = 1.4331 \times \rho_{RhoVol} - 0.1154 \quad (1)$$

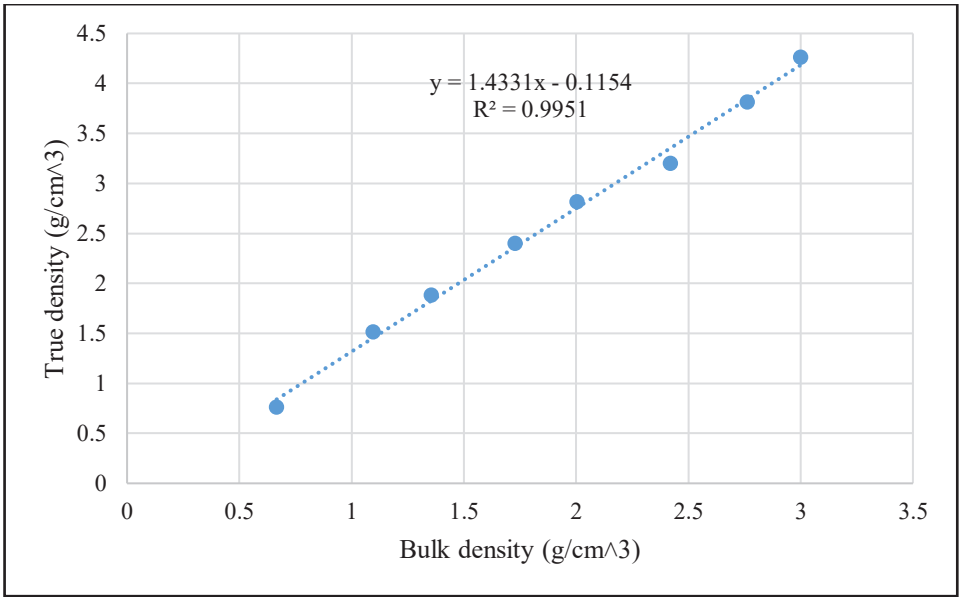
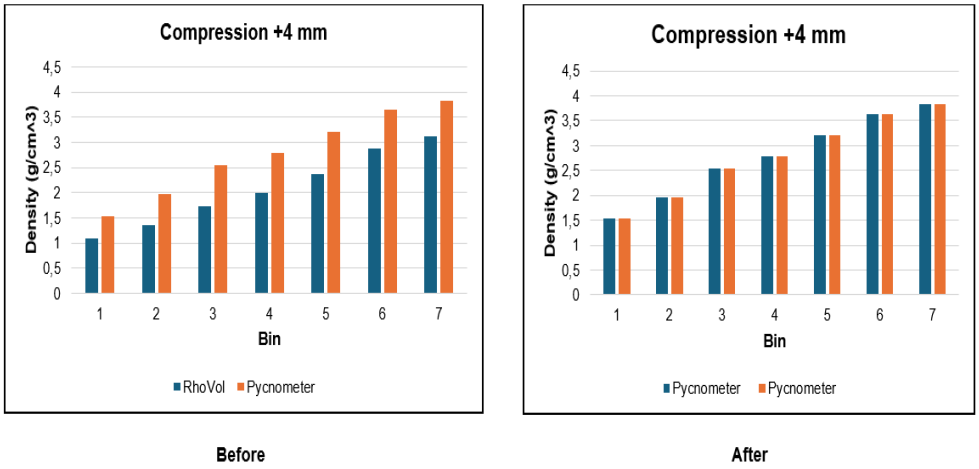


Fig. 4. Correlation between the calculated RhoVol bulk density and true density determined by helium gas pycnometer.

Error! Reference source not found. shows the uncorrected and corrected histograms of compressive crushed 4 mm top size particles after data calibration. The discrepancies were eliminated, and the corrected RhoVol densimetric data could be used in this analysis with confidence.



Before **After**

Fig. 5. Uncorrected and corrected RhoVol densities vs pycnometer density distributions of compressive breakage 4 mm top size particles.

3.3 The effect of compressive breakage and top size on coal liberation

Error! Reference source not found. shows the size by washability graph of 16 mm head sample crushed via compressive breakage to top size 3 mm. It can be seen in **Error! Reference source not found.** that the head sample is mainly composed of dense particles of relative density (RD) > 1.7. The relatively high RD of the particles may be because coal from the Waterberg coalfields is heavily interlayered and is composed of distinct mineral structures such as mudstones along with various coal bands (Jeffrey, 2005). The initial size reduction to top size 12 mm via compressive breakage resulted in a shift in the number of particles from high dense materials to middlings products (RD between 1.5-1.7). No coal products of RD < 1.4 were reported. Compressive breakage of the 12 mm particles to top size 8 mm significantly increased the number of clean coal particles (RD < 1.4) as compared to when crushing to 12 mm.

Compressive breakage to top size 8 mm drastically decreased the amount of high density (RD >1.8) particles to the middlings products (RD range 1.4 – 1.8). The increasingly shift to the middlings products with a reduction in top size was also observed when the particles were further subjected to compressive breakage to top size 6 mm. The latter was also observed with low RD products (RD <1.4). Compressive breakage from top size 8 mm to 6 mm increased the quantity of low RD products by 4.4%. The increase in the liberation of the middlings products after subsequent size reduction resulted in the increase the the amount of clean coal (RD <1.4). There is insignificant difference in the amount of clean coal products (RD <1.4) when the top size is reduced from 6 mm to 4 mm, indicating little further liberation. The amount of clean coal products is significantly improved when the particles are subsequently reduced in size from top size 4 mm to 3 mm. The increasingly shift in mass from high dense materials to middlings and low-density products was observed when the top size was reduced to 4 mm and 3 mm. Crushing to smaller top size however, may lead to the formation of fines. Fines are difficult to handle and may require further processing equipment that may render processes uneconomical [11].

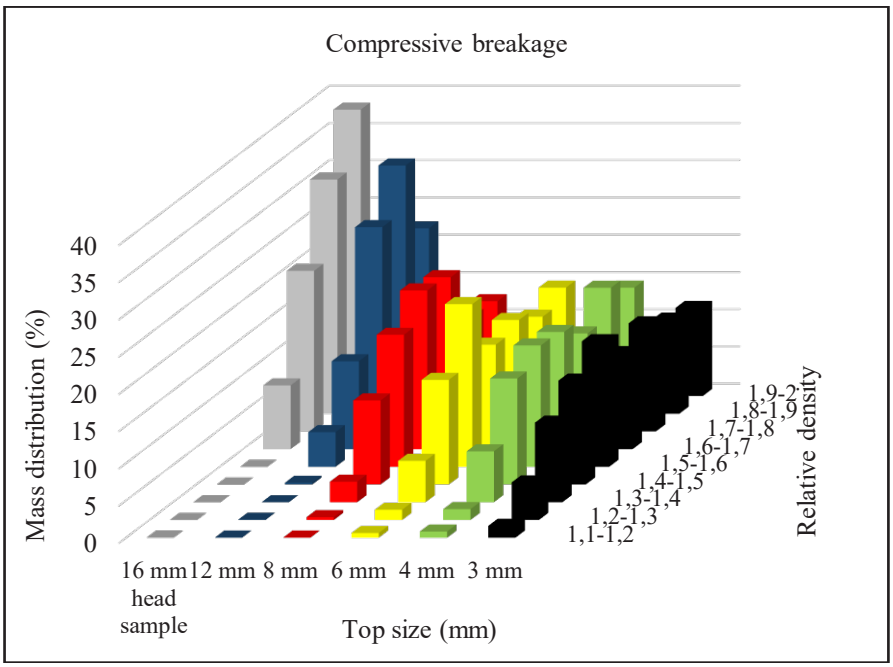


Fig. 6. Size by washability graph of 16 mm top size head sample crushed via compressive breakage to top size 3 mm.

Error! Reference source not found. shows the cumulative changes in the densimetric curve of the head sample undergoing compressive breakage to top size 3 mm. The densimetric curve further shows that the 16 mm head sample is mainly composed of near-dense particles necessitating the need for liberation. As seen in **Error! Reference source not found.**, the initial size reduction to top size 12 mm had a negligible effect on the liberation of clean coal products (RD <1.4) but resulted in the increase in the cumulative mass yield of middlings in the RD interval 1.5 - 1.8. Compressive breakage to top size 8 mm significantly increased the mass yield of clean coal products between the RD intervals 1.2 – 1.4. 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 crushing to top size 12 mm.

Subsequent size reduction to top size 6 mm further increased the mass yield of clean coal products. i.e. the mass yield improved from 14.4% to 21.6%. As previously observed, there is insignificant difference in the mass yield of low RD product (RD <1.4) when the top size is reduced from 6 mm to 4 mm. The mass yield of clean coal products is further improved when the top size is reduced to 3 mm. The mass yield of the middlings products is improved with a reduction in the top size. This gives an indication that the decrease in top size promotes coal liberation and improves the mass yield of clean coal products. This may be attributed to the elimination of mudstone/shale layers contaminating the coal with a reduction in the particles' top size.

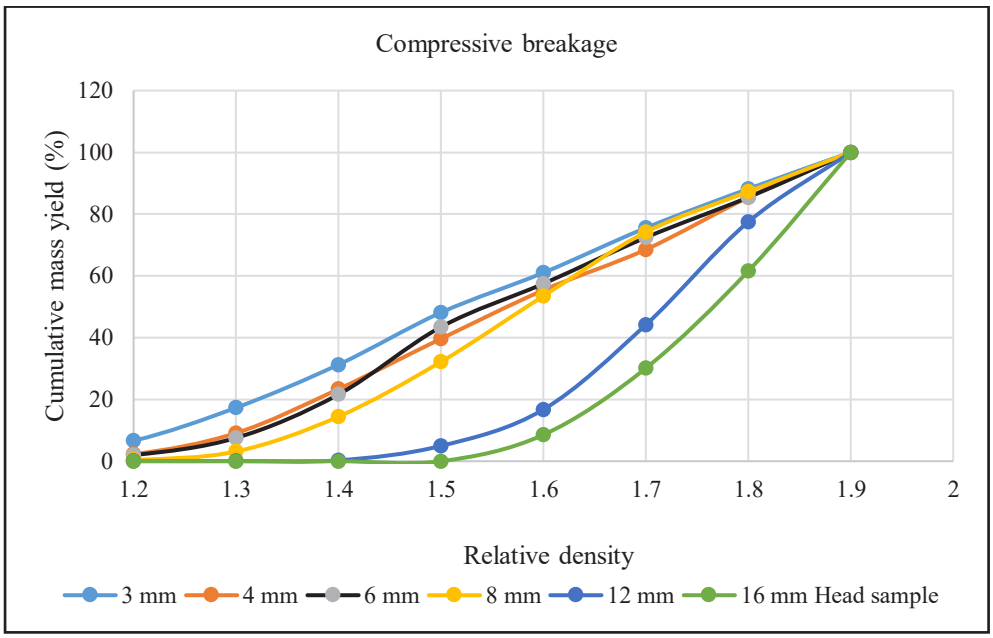


Fig. 7. Densimetric curve of compressive breakage 16 mm head sample to 3 mm.

3.4 The effect of impact breakage and top size on coal liberation

Error! Reference source not found. shows the mass distribution of the coal sample after the 16 mm head sample was subjected to impact breakage at top sizes 12 mm, 8 mm, 6 mm, 4 mm and 3 mm. As seen in **Error! Reference source not found.**, the 16 mm head sample is predominantly composed of near-dense particles. The initial size reduction to top size 12 mm resulted in a decrease in the amount of near-dense coal particles and an increase the middlings products. A small number of particles with RD < 1.4 were also obtained after the initial size reduction. Subsequent size reduction to size 8 mm significantly increased the quantity of clean coal particles (RD < 1.4). There is a 4.6% improvement in the mass distribution of clean coal products (RD < 1.4) when the top size is reduced from 12 mm to 8 mm. An increase in the quantity of middlings products was observed with a reduction in the top size.

Further size reduction to top size 6 mm, 4 mm and 3 mm increased the amount of clean coal particles while decreasing the number of middlings and dense particles. This shows that crushing to smaller to sizes increased the amount of clean coal product and decreased the number of dense particles. Crushing to smaller top sizes resulted in increased liberation of coal macerals from the gangue.

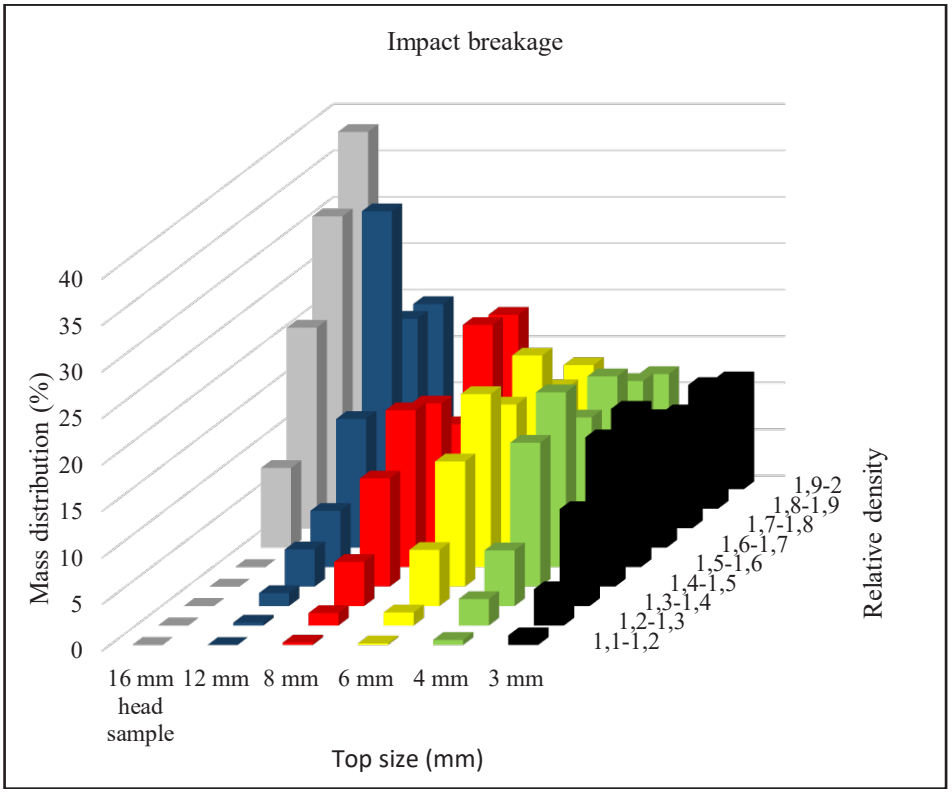


Fig. 8. Size by washability graph of 16 mm top size head sample crushed via impact breakage to top size 3 mm.

Error! Reference source not found. shows the cumulative changes in the densimetric curve when the 16 mm head sample was subjected to impact breakage to top size 3 mm. As seen in **Error! Reference source not found.**, there is a small increase in the cumulative mass yield of RD < 1.4 coal products after the head sample was subjected to the initial impact breakage to top size 12 mm. Subsequent size reduction to top size 8 mm resulted in a significant improvement in the mass yield of clean coal products in the RD intervals of between 1.2 – 1.4. There is a small increase in the mass yield of clean coal products between the RD intervals 1.2 – 1.4 when the top size is reduced to 6 mm and 4 mm. A notable increase the cumulative mass yield of clean coal products (RD between 1.2 – 1.4) was observed when the top size was reduced to 3 mm. Impact breakage of the head sample to smaller top sizes led to an improvement in the mass yield of low-density coal products.

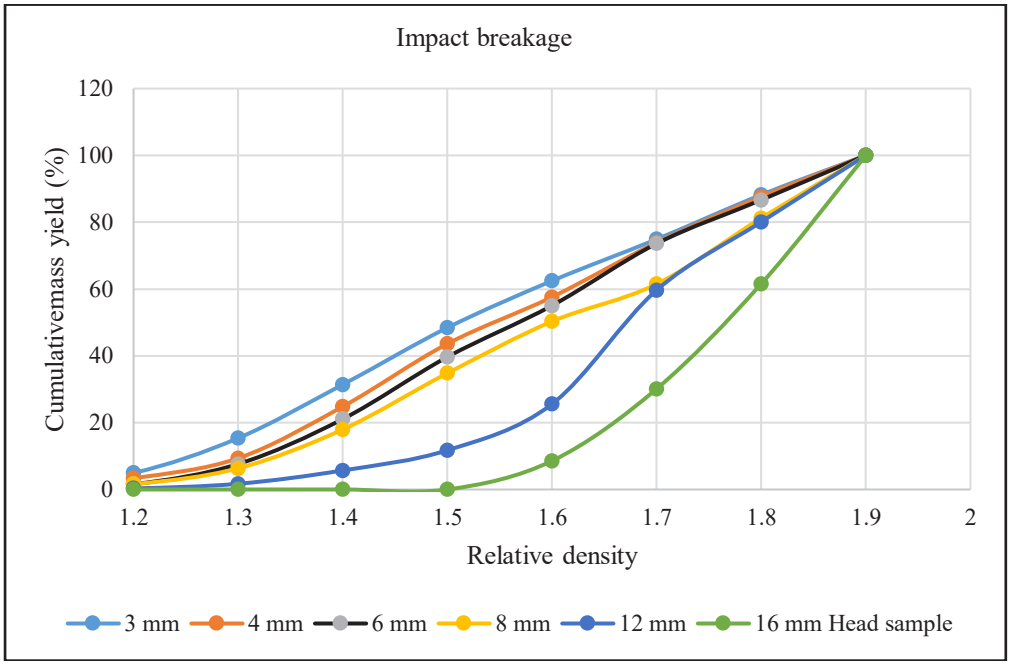


Fig. 9. Densimetric curve of impact breakage 16 mm head sample to 3 mm.

3.5 Comparison between compressive an impact breakage

3.5.1 Mass distribution comparison between compressive and impact breakage at different top sizes.

Fig. **10** shows the mass distribution comparisons between compressive and impact breakage at different top sizes. As seen in Fig. **10**, impact breakage of the head sample to top size 12 mm was more effective in the reduction of near-dense particles in the RD intervals 1.8-2 as compared to compressive crushing. Small proportion of clean coal particles were also observed after impact breakage to top size 12 mm as compared to compressive breakage. Compared to compressive crushing (about 3.4%), impact breakage to top size 8 mm produced a significant amount of clean coal of RD < 1.4 (roughly 6.3%). When the top size was lowered to 6 mm, there was a negligible difference in the quantity of clean coal particles released between compressive and impact breaking. Clean coal particle liberation increased from 3.4% to 7.55% when compressive breaking was performed to a top size of 6 mm, compared to 6.3% to 7.62% when impact crushing was used. The quantity of clean coal products that are obtained following compressive and impact breaking to top size 3 mm varies slightly. Following compressive breakage to 3 mm, 17.3% of coal products had an RD of less than 1.4, whereas 15.4% had an RD of less than 1.4 following impact breakage.

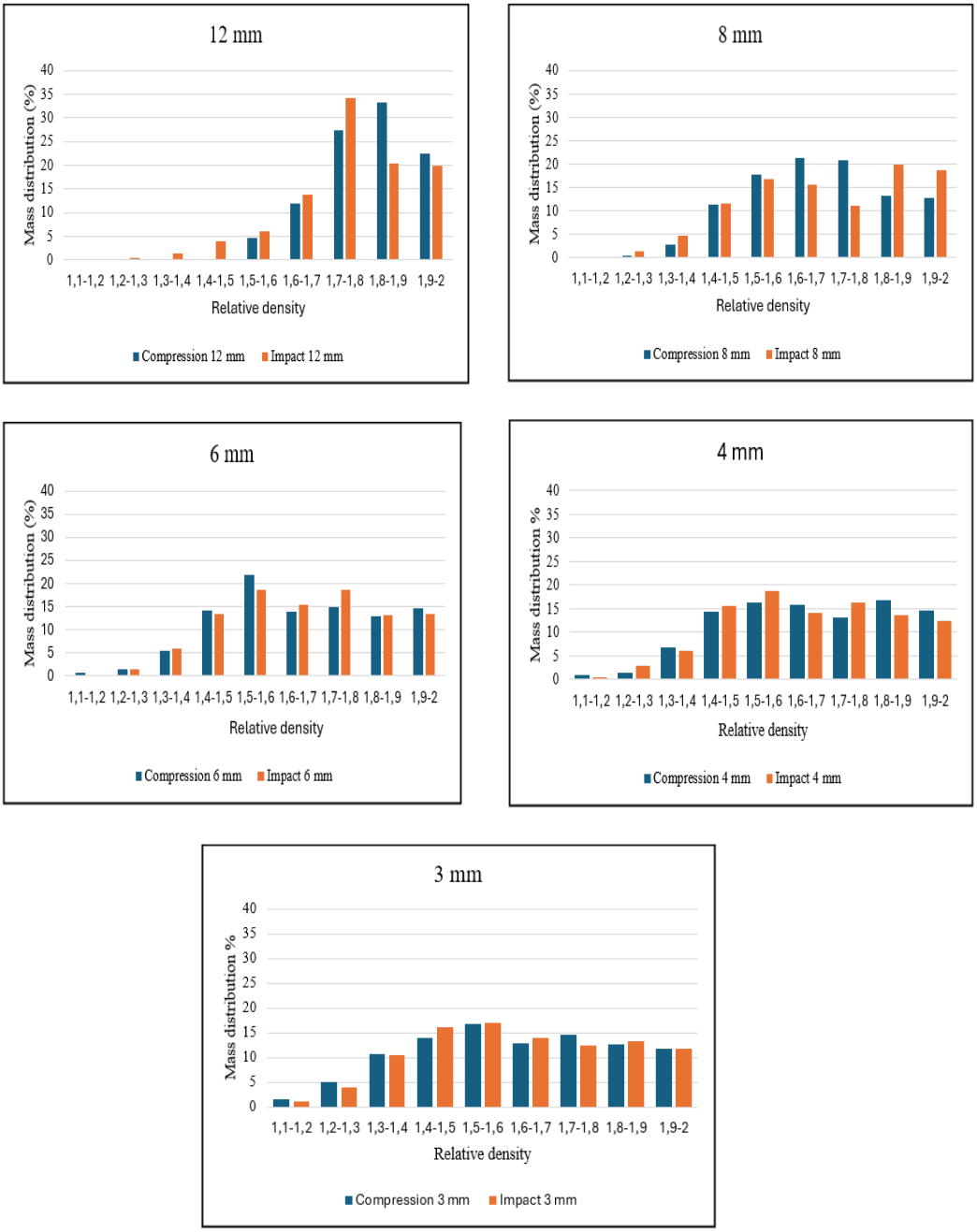


Fig. 10: Mass distribution vs density comparison between compressive and impact breakage at different top sizes.

3.5.2 Cumulative mass yield comparison between compressive and impact breakage.

The mass yield change following compressive and impact breaking of the 16 mm head sample at various top sizes is shown in **Error! Reference source not found.**. Assuming a RD cutpoint of 1.4, subjecting the head sample to compressive and impact breaking to top size 12 mm resulted in little increase in mass yield after compressive crushing as compared to the notable increase in yield in the case of impact crushing. The mass yield following compression and impact breaking was substantially boosted by the top size reduction from 12 mm to 8 mm. The mass yield rose from 0.28 to 14.4% following compressive breakage and from 5.7% to 17.9% following impact breakage. Impact breakage resulted in the highest mass yields after top size reduction to 8 mm. When the coal was crushed to 6 mm, there was a slight 0.6% variation in the mass yield favouring compressive breakage. When the coal was crushed to 4 mm for both breakage mechanisms, the mass yield slightly increased. No significant difference was observed between compressive and impact breakage when the coal was subsequently crushed to 3 mm. Impact breakage was more effective in the liberation of clean coal products at top sizes 12 mm, 8 mm, and 4mm.

The slight increase in the mass yield after compressive and impact breakage of the head sample to top size 12 mm may be attributed to the highly morphological structure and intercalated mineral matter associated with the Waterberg coalfield coal bands. The significant increase in the mass yield of clean coal products of RD <1.4 when crushing to 8 mm and 6 mm can be attributed to the liberation of clean coal products from the gangue with a decrease in the surface area of particles. This is in agreement with similar findings by [9]. They reported no significant effect on the mass yield after compressive and impact breakage to top size 13.2 mm whereas the yield was significantly improved when the coal was crushed to 6.7 mm [9].

Table 2. Mass yield comparison after compressive and impact breakage of the head sample at RD 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

3.5.3 Particle size distribution comparison

Fig 11 compares the cumulative passing percentage of particles versus particle size (mm) of compressive and impact crushed coal samples at different top sizes. It can be seen that the 12 mm impact breakage curve is slightly below that of the 12 mm compressive breakage curve between 7-12 mm particle size range. This indicates that impact breakage to top size 12 mm resulted in slightly finer distribution as compared to compressive breakage. There is negligible difference in the PSD curves of compressive and impact crushed 8 mm top size samples. Further size reduction to top size 6 mm resulted in a slightly finer PSD for the impact crushed sample as compared to compressive breakage. The latter was also observed when the top size was further reduced to 4 mm. There was no significant difference in the PSD curves of compressive and impact crushed coal sample when the top size was reduced to 3

mm. The particle size distribution is not affected by the method of crushing at this fine size. As particle 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 particle size distribution at finer sizes.

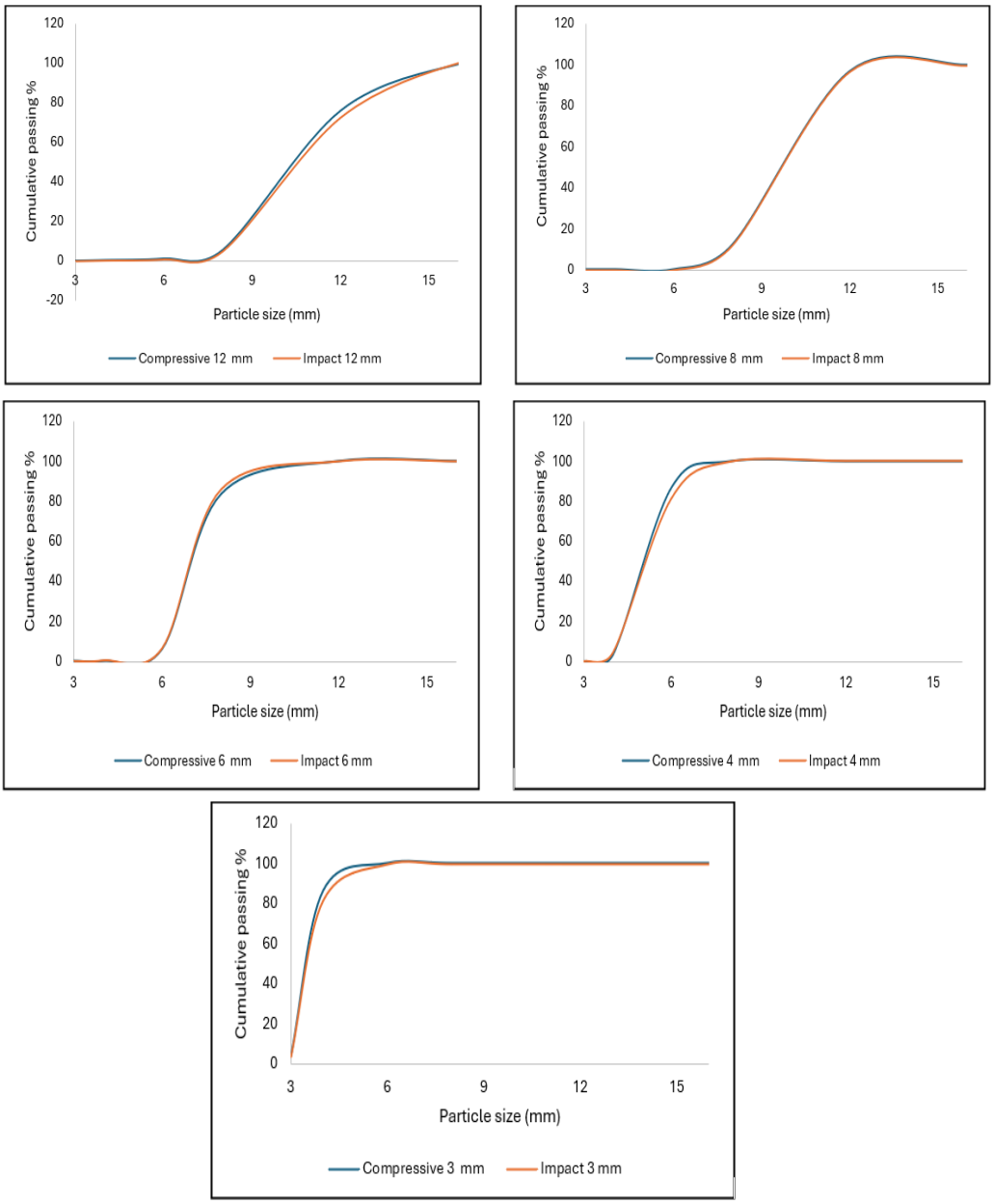


Fig 11: Particle size distribution comparisons between compressive and impact crushed coal samples

4 Conclusion

The RhoVol densimetric analyser was used to investigate the effect of compressive and impact breaking on coal liberation. Proximate analysis shows that top size 16 mm head sample has high ash content which necessitate the need for coal liberation. RhoVol densimetric analysis show that crushing the head sample to a top size of 12 mm had little effect on the mass yield of clean coal products for both breakage modes. When the top size was decreased to 8 mm and 6 mm, the mass yield of clean coal was significantly increased. Size reduction from 8 to 6 mm improved the mass yield of clean coal products by 7.2% for compressive breakage and 3.2% in the case of impact crushing. The mass yields for both breakage methods were not significantly affected by crushing to the top size of 4 mm. There is negligible difference in the mass yield of clean coal products when the top size was reduced to 3 mm for both breakage modes. PSD analysis show that impact breakage was more effective in the reduction of coarser agglomerates to finer particles as compared to compressive breakage. 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 particle size distribution at finer sizes. Compared to compressive breakage, impact breakage was more successful in the liberation of clean coal products and increased their mass yield.

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