

Innovative Approaches for Effective Utilization of Washery Middling

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Abstract

Coking coal plays a critical role in the iron and steel industry. It is a primary raw material for coke making. The depletion of high-grade coal reserves leads to a deterioration in the quality of raw coal, resulting in the generation of 35% - 40% middlings during the coal washing process. These middlings, known as washed power coal, are currently used by thermal power plants. However, they could be a potential source for clean coal recovery. The growing demand for cleaner coal with lower ash content presents challenges. Present investigation explored the processing of middling sample collected from the coking coal washery. Various processing techniques were employed to improve the quality of the middling sample in terms of ash content, calorific value and maceral content. Gravity separation using spiral concentrator followed by column flotation improved the product quality from 42.8% to 18% ash. The product showed improvement in the calorific value (6989.5 kcal/kg), vitrinite and inertinite contents, making the product suitable for coke production. This study highlights the potential to upgrade middlings for clean coal recovery, which could reduce coking coal imports.

Keywords

Coking Coal, Middling, Washability, Spiral Concentrator, Column Flotation

1. Introduction

Coking coal is a limited resource in India, with its demand in the steel sector increasing rapidly due to the expansion of existing steel plants and the establishment of new greenfield projects [1]. Meeting the demand for high-rank coking coal for

steel plants is a significant challenge. The quality of raw coal available for processing is steadily declining because of the depletion of high-grade reserves.

The middlings are the by-products generated from the conventional gravity separation process in coal washeries and usually contain an ash between 30% to 50% [2]. These middlings are known to be hard to reprocess because of their poor separation characteristics, high ash content, and low energy value [3]. In many cases, coal middlings are mixed with thermal fuel for power plants around the world. This practice leads to a significant waste of valuable resources, especially for the high-rank coking coals that have high demand [4].

Indian coking coal washeries typically produce three types of products: clean coal, middlings, and rejects. It has been observed that, due to the gradual depletion of high-grade raw coal, the generation of middlings is increasing daily. This increase leads to a decrease in the yield of clean coal in the washeries and results in a short supply of coking coal to the steel industry. In India, the middlings generated from coking coal washeries comprise about 40% - 50% of the total output and contain more than 3000 kcal/kg gross calorific value. They are one of the three by-products generated in a coking coal washery, along with clean coal and rejects. This represents a significant loss of resources, particularly for the high-quality coking coals used as fuel for power generation.

Currently, only 14% of India's coking coal requirements are met through domestic supply. In FY24, India imported 58.8 million tonnes of coking coal, up from 51.20 million tonnes in FY21 [1]. The middlings, which are being used for thermal power generation, need to be processed to recover the carbon content. These middlings are also known as "washed power coal". Middlings from coking coal washery are known to be difficult to reprocess due to their poor liberation characteristics and high ash content [5]. A few studies have explored the processing of washery middlings using high-voltage pulses to improve their processability. The breakage characteristics of middling samples were assessed using different methods to understand their liberation properties and potential for retreatment [6] [7].

The washery middlings are usually the heavy media cyclone product having a feed size in the range of 0.5 mm to 13 mm, sometimes 20 mm. Currently, these products are utilized for power generation, but they could also serve as a potential source for recovering carbon values, possibly making it a better feed than WV and WVI raw coal [8]. To conserve and sustain the scarce resource of coking coal, it is imperative to introduce new processes for the beneficiation of middlings generated from coking coal washeries in a cost-effective manner. However, there has been limited research conducted in India on the recovery of clean coal from the middlings of coking coal washeries. The washery middling samples were characterized only by washability study to assess the amenability to beneficiation. Preliminary work has been carried out using Mozley Mineral separator to find the response to processing [9]. This paper highlights potential methods for recovering the clean coal from the middling from one of the Indian of coking coal washeries in a large scale. The developed process aims to produce clean coal, which can meet

the industry's demand for coke making.

2. Materials and Methods

The coking coal washeries process the $-13 + 0.5$ mm/ $-20 + 0.5$ mm-sized coal fraction using a heavy media cyclone and generating three products like clean coal, middlings, and rejects. For the present study, the middling sample was collected from one of the Indian coking coal washeries located in Jharia. The collected sample was air-dried, and thoroughly homogenized. A representative sample was drawn for characterization and washability studies at various top sizes to assess the optimal feed size for conducting the beneficiation for ash reduction. The characteristics of the sample were determined using coal petrography, proximate analysis, and washability studies. Based on the washability results, the best feed size was selected for processing of the sample for achieving the clean coal with the desired grade.

The strategies employed for processing of the sample were gravity separator using a spiral concentrator, followed by column flotation. The -0.15 mm fines were processed separately with two different types of frother under varied conditions, like frother concentration, superficial air velocity, and froth height, to understand their response. Then, fines mixed with spiral middling product were processed together to improve the product yield. The generated product was characterized to assess the suitability for coke making.

3. Results and Discussion

Proximate analysis of the middling sample was determined using standard IS 1350 (Part-1): RA 2019. It has been found that the ash content of the sample is 38.8% with 19.9% volatile matter and 41.3% fixed carbon. The gross calorific value of the sample (air-dried basis) was determined using Bomb Calorimeter following ASTM D5865:2019 and found to be 4580 kcal/kg.

3.1. Coal Petrography

Petrography studies were carried out, taking a representative sample of washery middling for the investigation. The polished sections were prepared using epoxy, resin and hardener for the coal sample. The result of modal analysis is given in **Table 1**. From the microscopy observations (modal distribution analysis), it has been found that the given coal sample consists mainly of vitrinite maceral and the proportion of the inertinite macerals is comparatively lower than that of the vitrinites. The volume% of the mineral matters was found to be 38.62, which signifies the enrichment of the mineral matters in the given coal. The random reflectance (Rr%) is 1.25, which indicates that the coal sample is medium volatile coking coal in nature. **Figure 1** shows the distribution of the organic and inorganic phases of the coal sample. Most of the vitrinite and inertinite macerals have been observed to be interlocked with some mineral matters. The mineral matters have been seen as pore-filled, fracture-filled and interlocking in nature.

Table 1. Coal macerals and mineral matters distribution (vol%).

Maceral and mineral matters	vol%
Vitrinite	40.84
Inertinite	20.54
Mineral matters (M)	38.62

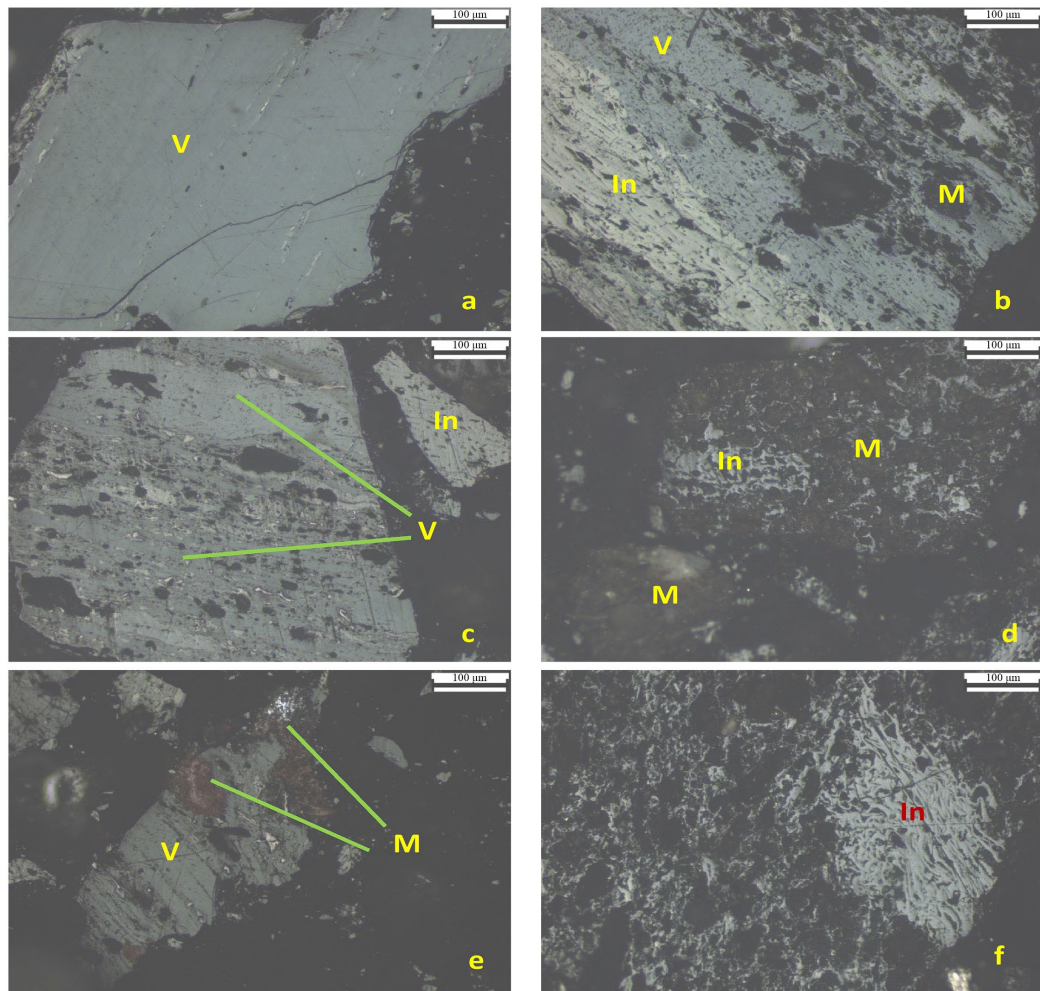


Figure 1. Distribution of different coal macerals and mineral matters present in middling sample. (a) Vitrinite maceral (V); (b) Vitrinite (V) and inertinite (In) macerals and some pore filled interlocked mineral matters (M); (c) Vitrinite (V) and inertinite (In) macerals; (d) Mineral matter (M) enriched grain containing some inertinite (In) macerals; (e) Some interlocked mineral matters (M) within vitrinite (V) maceral; (f) Inertinite (In) maceral.

3.2. Washing Characteristics of Middling Sample

The middling sample was crushed to three different top sizes, viz. –6 mm, –3 mm and –1 mm. The size analyses of the crushed samples are given in **Table 2**. It shows that, with the decrease in the top size of the sample, the ash content in the –0.5 mm or –0.15 mm fraction increases. Washability studies with all three different top sizes of middling sample were carried out.

Table 2. Size analyses of crushed middling sample.

Sample crushed to 6 mm				
Size, mm	Wt%	Ash%	Cum Wt%, Retd	Cum Ash%
-6 + 3	32.5	38.69	32.5	38.29
-3 + 0.5	52.5	38.42	85.0	38.52
-0.5	15.0	37.88	100.0	38.43
Sample crushed to 3 mm				
-3 + 0.5	79.8	38.53	79.8	38.53
-0.5	20.2	38.66	100.0	38.56
Sample crushed to 1 mm				
-1 + 0.5	58.4	38.74	58.4	38.74
-0.5 + 0.15	15.7	38.20	74.1	38.63
-0.15	25.9	38.79	100.0	38.67

3.2.1. Crushed to -6 mm and -3 mm

Usually, the washery middlings samples (Washed power coal) are interlocked coal particles that failed to respond to the gravity separation while treated in heavy media cyclone. They need adequate liberation to unlock the non-combustible substances (mineral matter) for generating the product with low ash. Therefore, it is very important to select the optimum feed size while processing of such samples will be carried out. In this case, top size of the middling sample received was -13 mm. Initially, the middling sample was crushed to top size of 6 mm and 3 mm. A washability study of -6 mm and -3 mm was carried out by varying the density of the medium from 1.4 to 2.0 gm/cm³. Ash content of all the products was analyzed based on dry-moisture-free basis. The washing characteristics of the crushed coal could be obtained from the weight% and ash% of the floats collected at different densities, as presented in **Figure 2**. It is found from **Figure 2** that washing characteristics of -3 mm feed size are marginally better than those of the -6 mm sample due to improved liberation. The product yield at 18% ash level is 3% higher for the -3 mm feed size compared to the -6 mm feed size.

3.2.2. Crushed to -1 mm

From the washability study, it is found that the product yield and ash content are not significant even at -3 mm feed size. Therefore, in view to improve the product yield and ash content, sample needs to crush further to increase the liberation characteristics. Therefore, it was crushed to -1 mm. In this case, washability studies were carried out for the fractions, viz. -1 + 0.5 mm and -1 + 0.15 mm to assess the maximum yield achievable at the targeted ash level from these fractions. The results are shown in **Figure 2**. The study shows that reducing the top size of middling sample to -1 mm is more effective than the other two top sizes (-6 mm and -3 mm) as it produces higher product yield at 18% - 19% ash level. **Table 3** shows that the product yield is less than 20% by weight at an 18% ash level when the top

size of feed is above 1 mm. The higher yield is found with $-1 + 0.15$ mm fraction, between the two different size fractions of -1 mm. The product yield is 28% by weight for the feed size of $-1 + 0.15$ mm, which is 13% more than that of the $-6 + 0.5$ mm feed size at 18% ash, and 10% more than the $-3 + 0.5$ mm feed size. **Figure 2** also shows that the $-1 + 0.15$ mm size fraction produces encouraging results at 18% and 19% ash levels among all the size fractions.

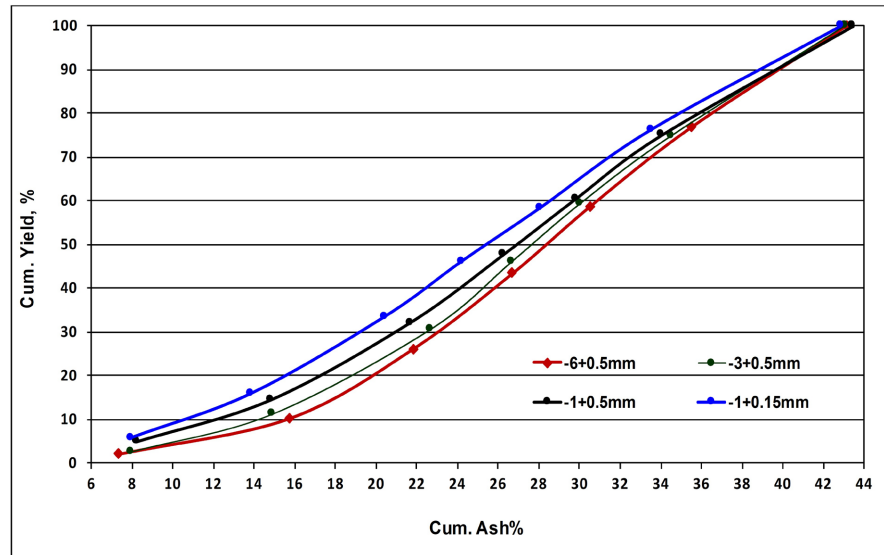


Figure 2. Washing characteristics of -6 mm, -3 mm and -1 mm crushed middling sample.

Table 3. Washability results at 18% - 19% ash level for different feed sizes.

Feed size, mm	Washed product (%) at 18% ash		Washed product (%) at 19% ash	
	Yield, %	S.G	Yield, %	S.G
$-6 + 0.5$	15	1.52	18	1.55
$-3 + 0.5$	18	1.55	20	1.55
$-1 + 0.5$	22	1.54	25	1.58
$-1 + 0.15$	28	1.56	30	1.58

3.3. Beneficiation Study

Based on the washability study, top size of the middling sample (washed power coal) was fixed at -1 mm to conduct the beneficiation studies for ash reduction. An attempt was made to process the sample by gravity separation, as it is one of the cheapest wet processing methods. Therefore, processing studies were conducted using spiral concentrator using $-1 + 0.15$ mm fraction to produce a clean coal product.

3.3.1. Spiral Concentrator

Spiral concentrators are devices used to separate solid components in a slurry form. The separation process is based on the combination of the density of solid particles and hydrodynamic properties, especially, drag force. In spiral concentra-

tor, different forces like gravitational, centrifugal, drag, lift and friction forces act on the particle during its passage down the curvilinear path of the spiral. The resultant of the forces governs the separation of particles on the spiral deck depending on their size and density. Spiralling of $-1 + 0.5$ mm and $-1 + 0.15$ mm were performed at 10% solid concentration. From the results of spiralling (Table 4), it is found that the response of $-1 + 0.15$ mm is better than that of $-1 + 0.5$ mm feed size. The product yield is 4.3% (w.r.o.) less for the $-1 + 0.5$ mm feed size, as the weight% in the narrow size range ($-1 + 0.5$ mm) is less, resulting in a lower product yield with respect to the feed content. The product yield for $-1 + 0.15$ mm feed size is 11.7% with the respect to the original feed with ash content of 19.34%. The tailing generated from spiral concentrator is 31.4% by weight with 51.95% ash. It shows that effective rejection is achievable through gravity separation using spiral concentrator. The spiral middling obtained from $-1 + 0.15$ mm feed size is 31.0% by weight with ash content of 31.45% and used for column flotation studies with the fines of -0.15 mm (38.07% ash), removed from the crushed to -1 mm sample. The fines were also processed separately to study their response with different types of frother.

Table 4. Results of spiral concentrator using feed sizes of $-1 + 0.5$ mm and $-1 + 0.15$ mm.

Products	Concentrate	Middling	Tailing	Concentrate	Middling	Tailing
	$-1 + 0.5$ mm			$-1 + 0.15$ mm		
Assay						
Wt, %	12.7	49.9	37.4	15.7	41.9	42.4
WRO*	7.4	29.1	21.8	11.7	31.0	31.4
Ash, %	19.77	33.59	50.92	19.34	31.45	51.95

WRO: With respect to original feed.

3.3.2. Processing of Fines (-0.15 mm) Removed from -1 mm Crushed Coal

The -0.15 mm fraction separated out from -1 mm coal during the crushing of the middling sample contains 38.07% ash. To reduce the ash content, it was processed using column flotation under varied conditions. The feeding and tailing flow rate were kept at 1.5 lpm and 3 lpm, respectively. Diesel oil was added as collector along with the sodium silicate as depressant. While conducting the tests, variables kept constant are pulp density of solid at 10%, sodium silicate at 3.5 kg/t, diesel oil at 210 g/t and wash water flow at 0.25 lpm.

1) Effect of Froth Height

Column flotation studies were carried out with the fines (-0.15 mm) varying the froth height between 15 cm and 35 cm. The effect of MIBC concentration was studied at 65 g/t and 80 g/t with the froth heights. Figure 3 shows that higher dosage of 80 g/t MIBC increases the product yield (36.9%) significantly with high ash content (31.33%) at lower froth height of 15 cm. This signifies that increasing froth height reduces the floatability of less hydrophobic particles (gangue) than the more hydrophobic coal particles due to the weaker bonding. At higher concentra-

tion of MIBC (80 g/t), the product ash was found to be as ash as 22.51% even at higher froth height of 35 cm. This indicates that increased frother dosage not only increases the hydrophobicity of the desired particles but also increases the entrainment of the undesirable particles (gangue); thus, leading to lower product quality. The lower dosage of MIBC (65 g/t) produces low ash product at all point of froth height when compared with higher dosage. At froth height of 35 cm and 65 g/t of MIBC, the product ash level significantly reduces to 18.4% which is quite encouraging. The high froth height in flotation column reduces the tendency for unselective flotation, minimizing ash content in the product and reduces the tendency for unselective flotation. This reveals that a lower concentration of frother leads to less entrainment of gangue materials into the froth, due to relatively less stability of the froth [10]-[12].

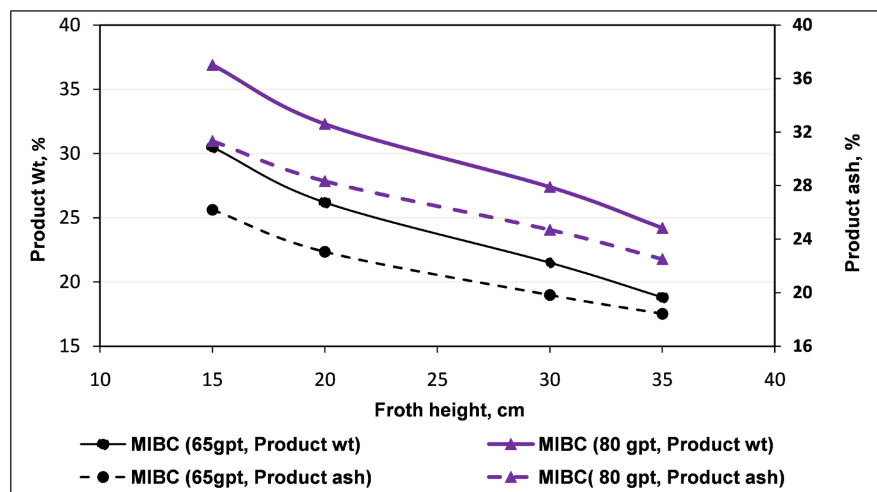


Figure 3. Effect of concentration of MIBC and froth height on product recovery.

2) Effect of Frother Types

The response of -0.15 mm fraction in a column flotation was compared using two different types of frother, like Methyl Iso-Butyl Carbinol (MIBC) and Synthetic Frother (SF) from Nalco (Figure 4). Flotation tests were also conducted at different Superficial Air Velocity (SAV), keeping the froth height constant at 20 cm.

MIBC: The performances of MIBC and SF under varied conditions are presented in Figure 4. It shows that the flotation performance of MIBC is superior, even at higher SAVs. The results from Figure 4 indicate that MIBC produces very low yields at higher froth depths, attributed to the decreased stability of the froth. MIBC offers better selectivity, leading to lower ash content even at higher superficial air velocities. The findings suggest that MIBC is preferable to use where both product recovery and quality are predominant.

Synthetic Frother (SF): In contrast, while SF produces a high yield, it is associated with higher ash content. This disparity indicates a potential issue with selectivity; SF might enhance the floatability of both the target minerals (coal) and undesirable gangue minerals, leading to increased ash content in the final product.

The use of Synthetic frother provides high yields but at the expense of increased ash content.

3) Impact of Superficial Air Velocity

The impact of superficial air velocity on product yield and ash content at a 20 cm froth height for MIBC, and at 20 cm and 30 cm froth heights for SF, is shown in **Figure 4**. A strong frother produces stable froth, which hinders the drainage of water and fine particles, leading to less gangue rejection and consequently lower product quality. At lower superficial air velocity, MIBC shows to be quite effective in optimizing both yield and ash content of the products. This efficiency indicates that at reduced SAV, MIBC provides better particle-bubble attachment and flotation selectivity, allowing for a more concentrated product, which is a critical role for achieving a good recovery.

SF, being a stronger frother, produces a more stable froth than MIBC [13] [14]. The effect of SF at increased froth height (30 cm) revealed that at low Superficial Air Velocity (SAV), the product ash content could be reduced to 5% compared to that at a low froth height of 20 cm. However, the product yield increases significantly with an increase in SAV. This signifies that increasing SAV can enhance the floatability of less hydrophobic particles (gangue) and, therefore, causes more entrainment in the product [15].

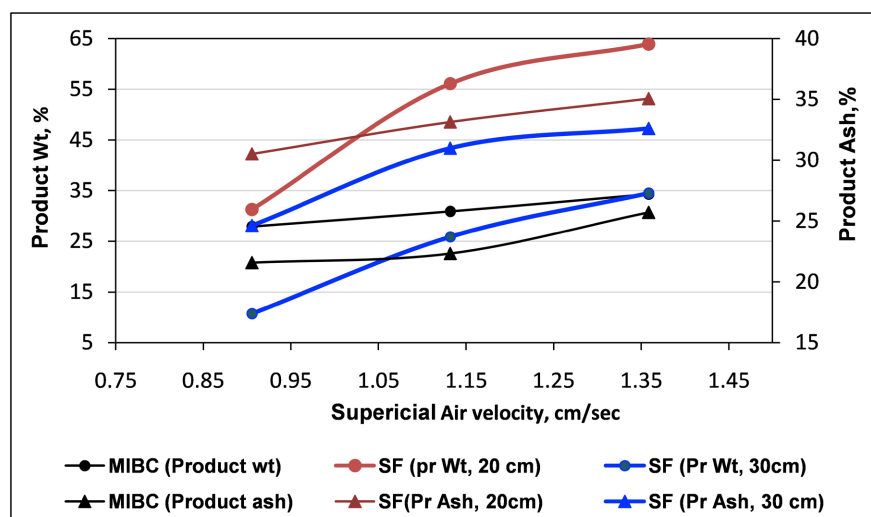


Figure 4. Effect of superficial air velocity on product yield and ash of fines.

3.3.3. Column Flotation with Spiral Middling and Fines

To increase the product yield, the middling product generated from the spiralling of the $-1 + 0.15$ mm fraction was treated with the fines. The spiral middling constitutes 31.0% by weight, with an ash content of 31.45%. This amount is significant and also contains carbon values. This product could be further processed after grinding it to 0.15 mm. The composition of the feed used for the column flotation is provided in **Table 5**. MIBC was used in the subsequent tests to achieve a product with low ash content due to its suitability, especially in the present study. Column flotation tests were carried out using reagents such as diesel oil (210 g/t) as a collector,

sodium silicate (3.5 kg/t) as a depressant, and MIBC (50 g/t) as a frother.

Table 5. Composition of feed for column flotation.

Product	Wt, % (WRO)	Ash, %
Spiral middling	31.0	31.45
-0.15 mm removed from -1 mm	25.9	38.07
Total	56.9	34.46

The experiments were carried out by varying the superficial air velocity for two different froth heights (20 cm and 30 cm) to get the desired product with good recovery. The effect of superficial air velocity on product yield (presented with respect to original feed) and their ash content is given in **Figure 5**. Similar trends are observed for two froth heights. It is found that higher air flow rate increases the product yield with increase of ash content due to the entrainment of the impurities [16]. It could be possible to get product with 17.48% ash with yield of 13.5% at 30 cm at high froth depth. The very low SAV and high froth height are not favourable for the mineralised bubble to reach the froth level. Thus, reduces the product yield.

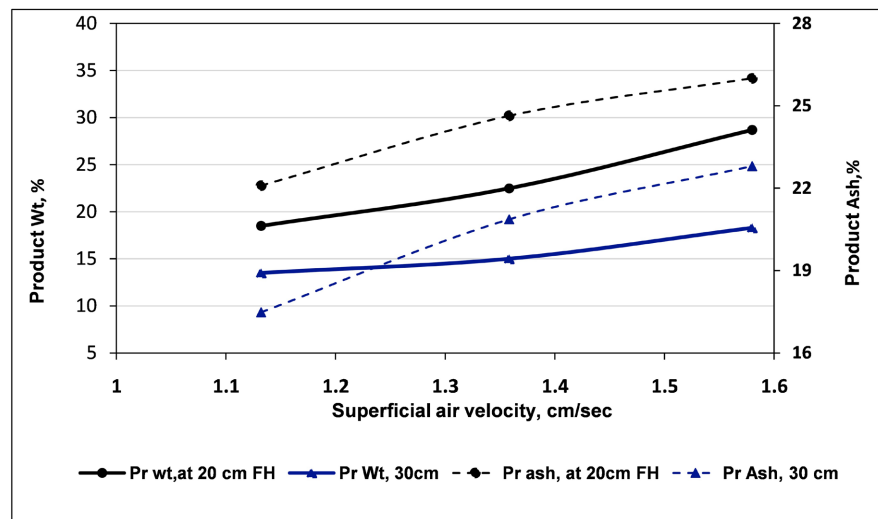


Figure 5. Effect of superficial air velocity and froth height on composite feed of spiral middling and -0.15 mm fines.

Table 6. Processing results using spiral concentrator and column flotation.

Processes	Products	Wt, %	Ash, %
Spiralling: Feed size: -1 + 0.15 mm	Sp. Concentrate	11.7	19.34
	Sp. Mid	31.0	31.45
	Sp. Tailing	31.4	51.96
Column Flotation: Feed: -0.15 mm fines & spiral middling Wt: 56.95%; Ash: 34.46%	Concentrate	13.5	17.48
	Tailing	43.4	38.32
	Total Concentrate	22.2	18.46

The outcome of the processing of middling sample using a spiral concentrator and column flotation is summarised in **Table 6**. The product yield of 11.7% with 19.34% ash could be obtained from the gravity separation using $-1 + 0.15$ mm. Flotation of composite feed of -0.15 mm generates 13.5% product with 17.48% ash. Thus, final product becomes 22.2% by weight, with 18.46% ash that could be produced.

3.3.4. Petrography Study of Washed Coal Product

The final product thus generated from processing of middling sample was characterised for its coking property. The quality of washed product was measured by petrographic study. The phase distribution, *i.e.*, modal analysis of coal macerals, mineral matters, reflectance measurement and photomicroscopy were carried out under both reflected and fluorescent light using a conventional polarized microscope. From the microscopy observations, it has been found that, vitrinite group of macerals dominates in the respective sample. Their proportion (45.17 vol%) is received to be more than the inertinite group of macerals (29.29 vol%). The relative concentration of the mineral matters has been found to be lower (25.54 vol%) than the macerals. The macerals are seemed to be free from interlocking characteristics (**Figure 6(a)**, **Figure 6(b)**). However, some pore space filled with alumino-silicate minerals (**Figure 6(c)**, **Figure 6(d)**) is observed in the washed sample. From the random reflectance measurement, the rank of the given coal was observed to be medium volatile coking coal (Rr% of 1.30). The result of modal analysis and mean random reflectance measurement is given in **Table 7**. The product quality was also measured in terms of calorific value and found to be 6989.5 kcal/kg.

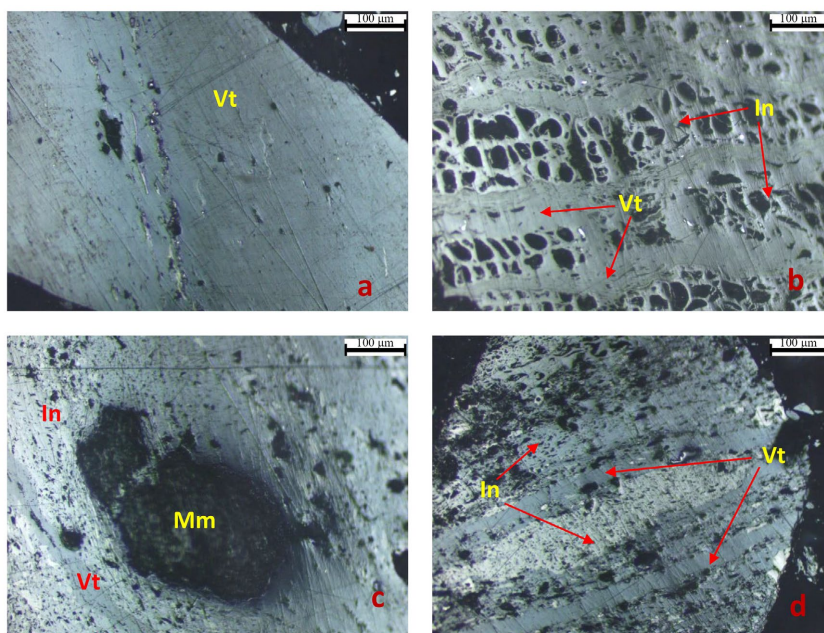


Figure 6. Photomicrographs showing distribution of macerals and mineral matters in washed coal sample. (a) A typical vitrinite maceral (Vt) with some fine layers of inertinite maceral and pore filled mineral matters; (b) Inertinite (In) and vitrinite (Vt) macerals; (c) A typical interlocked grain of vitrinite (Vt), inertinite (In) and mineral matters (Mm); (d) Bands of vitrinite (Vt), inertinite (In) macerals and pore filled interlocked mineral matters (Mm).

Table 7. Modal analysis (macerals and mineral matters distribution) (vol%) and mean vitrinite reflectance (Rr%).

Maceral and mineral matters	Vol (%)	Random reflectance (Rr) %
Vitrinite	45.17	1.30
Inertinite	29.29	
Mineral matters	25.54	

4. Conclusions

Coal being a low-cost material, its processing steps should be simple and utilize high-throughput separators. The processing of washery middling presents a promising opportunity for sourcing raw materials for coke production. This study emphasizes that adequate liberation is essential for effectively separating gangue minerals from coaly materials. Both gravity separation using spiral concentrators and flotation through column flotation have shown impressive results in reducing ash content while recovering carbon values. The key findings of the study are as follows:

- Spiral concentrators are highly efficient and capable of processing material finer than 1 mm at a high throughput.
- In spiral concentrators, a combination of gravitational, centrifugal, drag, lift, and friction forces acts on particles as they traverse the curvilinear path of the spiral. The resulting force dynamics determine the separation of particles based on their size and density.
- The use of column flotation for fine materials, combined with a depressant like sodium silicate, significantly enhances product quality.
- The choice of frother plays a critical role in the efficacy of column flotation processes.
- To achieve low ash content in the product, it is crucial to minimize the dosage of the collector while adjusting the frother dosage accordingly. The lower dosage of MIBC combined with appropriate froth heights can produce a cleaner product with reduced impurities, even as it may impact overall yield.
- Elevated superficial air velocity and reduced froth height tend to increase the ash content of the product.

The generated product with 18.4% ash content is suitable for industrial applications when blended with low-ash coking coal to achieve the desired ash level. This product can also be usable for small to medium blast furnaces, foundries, and other metallurgical uses where the operating conditions are less stringent. The use of this product may reduce reliance on imported coke. Overall, these findings highlight the potential of processing of washery middlings as a valuable resource for coke manufacturing through effective separation methods. Integrating improved beneficiation strategies into industrial plants can enhance coal resource utilization and minimize environmental impacts.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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