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Investigating the effect of lip froth washing on coal yield during flotation of a high ash South African coal

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Abstract: An investigation was conducted to evaluate the effect of lip washing on coal flotation at Anglo American's Goedehoop South (GHS) fine coal plant in South Africa. In the test-work, performance of cells with lip washing system were compared with baseline cells without lip washing in terms of coal yield and coal quality. Yields observed with lip washing were significantly higher than those of baseline cells. Improvements of up to 15% were recorded. The product obtained at low flotation reagent dosages (1.30–1.45 kg/t) on lip wash cells had ~16.85% ash content against ~17.65% with baseline cells, suggesting that higher yields could be achieved at superior qualities to those achieved with baseline cells. At higher reagent dosages (1.60–1.75 kg/t), coal yields further improved but quality reduced on lip wash cells. Calorific Values (CV) of coal products obtained by lip washing and baseline flotation were similar. When different coal particle size fractions were floated separately, the yield increased as particle size increased from 75 to 300 µm and then decreased from 300 to 500 µm for both baseline and lip washing flotation. Lip washing caused a marked increase in the yield for finer particles (< 300 µm) with optimum size class of between 212 – 300 µm. In addition, a much bigger increase in the yield was achievable with lip washing of lower quality coal. The ash content after lip washing of poor-quality coal were also comparable to the ash content after lip washing of good quality coal.

Keywords: flotation, mechanical flotation cells, flotation reagents, lip froth washing, coal yield, primary & secondary wash cells

1. Introduction

The beneficiation of South African coals generates large quantities of ultra-fines which have been previously discarded as waste material in the form of ultrafine slurries (Reddick et al., 2007). The disposal of ultra-fines has a negative impact on the environment as it pollutes water bodies through leakage of acid mine drainage caused by sulphur in the coal ultra-fines and ultra-fines dump footprint also uses up land that could be used for other purposes. The loss of combustible value with ultra-fines also results in loss of revenue for the coal mining companies (Han et al., 2021; Honaker et al., 2013; Kumar and Kumar, 2018; Reddick et al., 2007; Zhang et al., 2021b). Therefore, recovery of ultra-fines in coal processing can boost revenues for the coal processing industry whilst reducing the environmental footprint and improving sustainability of coal mines (Han et al., 2021; Harbort and Alexander, 2006; Honaker et al., 2013; Kumar and Kumar, 2018; Sibanda et al., 2020; Zhang et al., 2021b).

Flotation offers a viable proposition to recover coal from ultrafine coal waste as other technologies deployed for coal washing like dense medium separation (DMS), and spirals are not effective for recovery of ultrafine fraction of coal (Wang and Li, 2020). Flotation utilises the difference in

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hydrophobicity between the valuable mineral and discard material (gangue) to separate the product from the discard (Bournival and Ata, 2021; Sibanda et al., 2020; Wang and Li, 2020; Wills and Napier-Munn, 2006). Flotation is now a mature technology which gained momentum in the early twentieth century because of the fast depletion of high-grade ores leaving behind "not so easy" to process low grade and complex ores which required new technology to exploit. Flotation has been used to separate mainly sulphide minerals of copper, nickel, zinc, lead, cobalt and platinum group metals (PGMs) from their host gangue after size reduction (Feng et al., 2019; Han et al., 2021; Zhang et al., 2021a, Zhang et al., 2021b). Recovery of minerals by flotation has now been extended to oxide minerals as new flotation reagents continue to be developed. Flotation can either be direct flotation where the mineral of interest is recovered in the froth or reverse (indirect) where the mineral of interest is left in the slurry phase and gangue is recovered in the froth and discarded (Sibanda et al., 2020; Wang et al., 2021).

The recovery of coal by flotation is possible due primarily to the high natural hydrophobicity of coal and also due to the availability of reagents that can promote the flotation of coal (Bournival and Ata, 2021; Fuerstenau and Pradip, 1992). Investigations have shown that while South African ultra-fine coal can be beneficiated by flotation (Fickling, 1985; Reddick et al., 2007), it has proved to be more difficult to float due to the low rank of South African coals. Low rank ultra-fines have been found to require substantially large amounts of flotation reagents to be floated successfully which leads to higher reagent costs per ton of coal washed and higher operational costs (Jeffrey, 2005; Reddick et al., 2007). Consequently, flotation processes for South African ultra-fine coals need to have high efficiencies to ensure that recovery process remains viable (Opperman et al., 2002; Peatfield, 2003).

In 2007, a flotation plant was commissioned at the Anglo American's Goedehoop South (GHS) plant in Mpumalanga, South Africa for the treatment of coal with particles of size 212 μm and below (coal fines and ultra-fines). This was due to a response to the economic environment which necessitated evaluation of opportunities of treatment of ultra-fines in coal to increase revenue and profits to enhance the sustainability of coal business. The target coal product quality in the plant was set at ca. 27.30 MJ/kg calorific value (CV) on air dry basis (adb), which has been achieved satisfactorily, however the challenge is to try and increase coal yields while maintaining the achieved product quality. This objective led to the conceptualisation of this current study, and lip froth washing on the adapted mechanical flotation cells was selected as a technique to achieve this objective.

Lip froth washing is when clean water is sprayed onto the froth on the peripheral of the flotation cell, just inside the froth overflow lip, to remove hydraulic entrained ash particles (gangue) from the froth, Fig. 1 (Bennie, 2013). Adding wash water to the cell lip is one of the most crucial places for wash water addition because the entrainment is most severe at that point (Moys, 1978). Froth washing in the coal flotation industry has been applied to column flotation cells, but little application of froth washing has been reported on conventional mechanical cells.

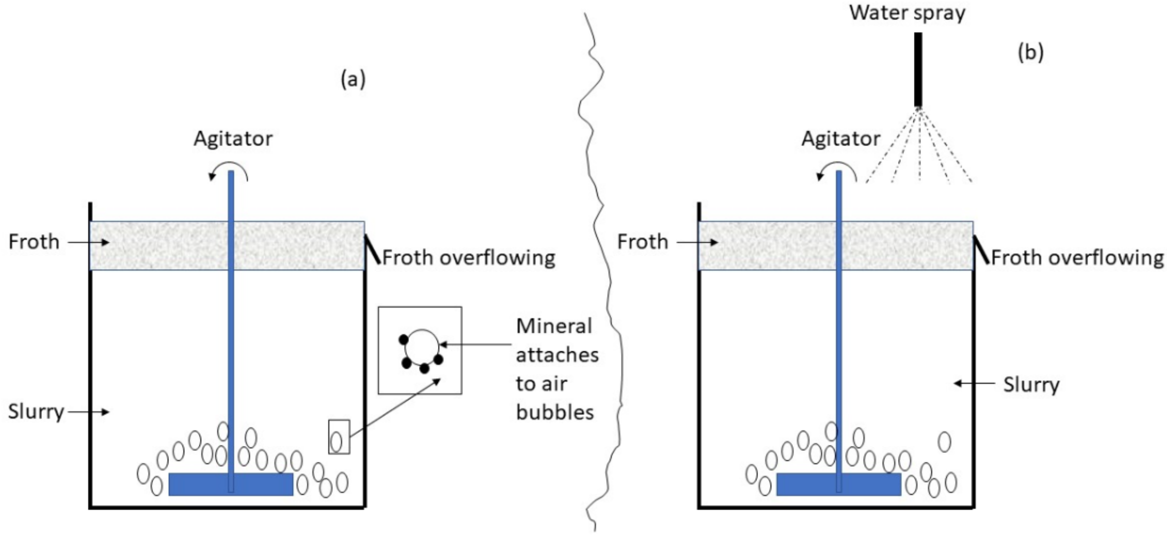

Fig. 1. Flotation Process (a) Operation of a conventional mechanical flotation cell and (b) mechanical flotation with lip froth washing (Adapted from Wang and Li, 2020; Wills and Napier-Munn, 2006)

Lip froth washing is usually done to increase the grade of the concentrate by removing gangue particles which accumulate in the froth by hydraulic entrainment (Finch and Dobby, 1990). With the use of lip washing water, it has been found that the bubble size tends to remain uniform because of the reduction in coalescence, this has been found to lead to improved froth stability and generation of small bubble sizes resulting in improved product qualities (Lahey et al., 2007; Nkolele, 2004; Kumar and Kumar, 2018; Lahey et al., 2007). In South Africa, limited trials have been conducted on the application of lip froth washing on fine coal flotation (Opperman et al., 2002).

The present study was undertaken in an attempt to improve the ultra-fines flotation recovery process at the GHS Flotation plant. The objective of this research was to design a suitable and effective lip froth wash system and evaluate whether lip washing can improve yield while maintaining the target product quality of ca. 27.30 MJ/kg CV (adb). The test-work compared lip washing to the current plant practice without lip washing. Both the lip washing line and the current plant practice line were fed from the same head box i.e. they were fed with the same coal feed material. The line without lip washing was run at the optimum plant operating parameters which represents the current plant performance while on the lip washing line combined primary and secondary (PW + SW) wash configuration was tested. This configuration is illustrated in Fig. 3. It is anticipated that results from such a study will have a positive effect towards the optimization of ultra-fine coal flotation in the South African coal industry.

2. Experimental test-work

2.1. Lip froth wash design

A lip washing system was considered, designed and tested as a potential froth wash design system for GHS flotation plant. Fig. 2 illustrates the lip washing design fitted to a dual cell for the experimental runs. The design of the lip washing system consisted of a 16 mm (ID) high density polyethylene (HDPE) ring installed around the cell lip. The ring was positioned 50 mm inside the cell lip and mounted 100 mm above the cell lip by means of HDPE braces. Holes with a diameter of 4 mm were drilled every 10 mm around the ring to inject wash water downwards. The water was introduced above the froth layer directly downwards to wash entrained material out of the product froth before the product froth overflowed over the cell lip to product launders. The water flow was adjusted to 4.5 m^3/h, producing a steady stream of water that was evenly distributed around the cell. All test-work was done at this wash water flowrate.

The hole size, distance between the holes and the water flowrate used in the flotation test-work were established via an off-line trial and error exercise that was intended to produce a steady stream of water that was evenly distributed around the cell and also to ensure that water did not remain on top of the froth but instead moved through the froth phase into the pulp phase.

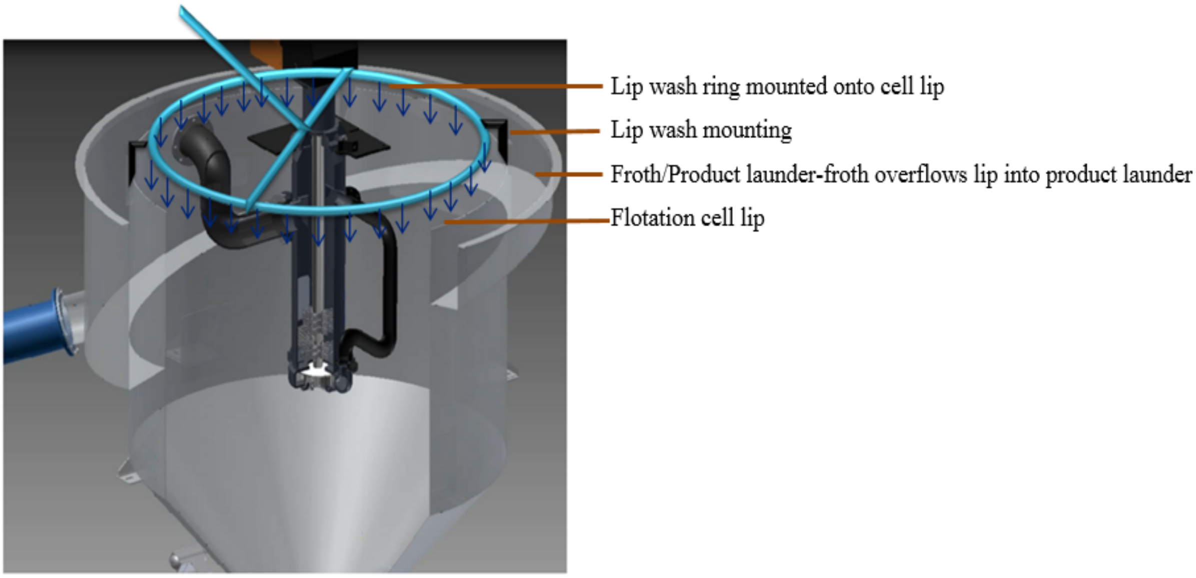

Fig. 2. Lip washing design fitted to the dual cell

Wash water used for lip froth washing test-work was fresh water. Fresh water was preferred over process water as it is free of particulate matter, process water normally contains particulate material, which is not entirely eliminated during solid-liquid separation, these particles can potentially block the small holes on the lip wash-pipes and render the lip washing ineffective.

2.2. Experimental design

The main objective of the test-work was to compare the current flotation plant performance with flotation that incorporates lip froth washing. The current flotation plant practice (without lip washing) was used as the baseline. The strategy to improve yield was pursued by increasing the flotation reagents dosage rates with the intention to float more coal particles and then simultaneously applying wash water to remove impurities and entrained gangue from the froth. The desired effect would be to increase the removal of entrained ash from the froth (by means of lip washing) while floating more coal by increasing reagents dosage rates. This could result in increased yields in mechanical coal flotation cells while hopefully maintaining the required product quality.

2.2.1. Flotation cells

To achieve this, two identical flotation lines in the current plant were chosen and named A1 and A2. The two lines are identical in design, and the test and inspection at commissioning demonstrated that they operate exactly the same.

One of the flotation lines, A2, was modified by retrofitting lip washing rings on the flotation cells. The other line, A1, referred hereto to as the baseline, had no lip washing mechanism fitted to it and was operated at the optimised plant operating conditions in the test-work. Both lines A1 and A2 were fed from the same head box and therefore received the same feed material at any given time in terms of feedrate and composition. Historic plant data before the lip wash mechanism was retrofitted into line A2 and it showed that A1 line and A2 had similar performance with no variation between them suggesting that the A1 line can reliably be used as a baseline against which the impact of lip washing on line A2 can be measured.

Fig. 3 illustrates the test-work process flow diagram showing the experimental setup and sampling points. The conditioned flotation feed material from the head box F was fed evenly into the primary flotation cells, the concentrate streams from the primary flotation cells overflowed into the concentrate launder of the secondary cells combining the two concentrate streams. The tailings from the primary flotation cells were re-floated in the secondary cells. The tailings from the secondary cells formed the final discard stream.

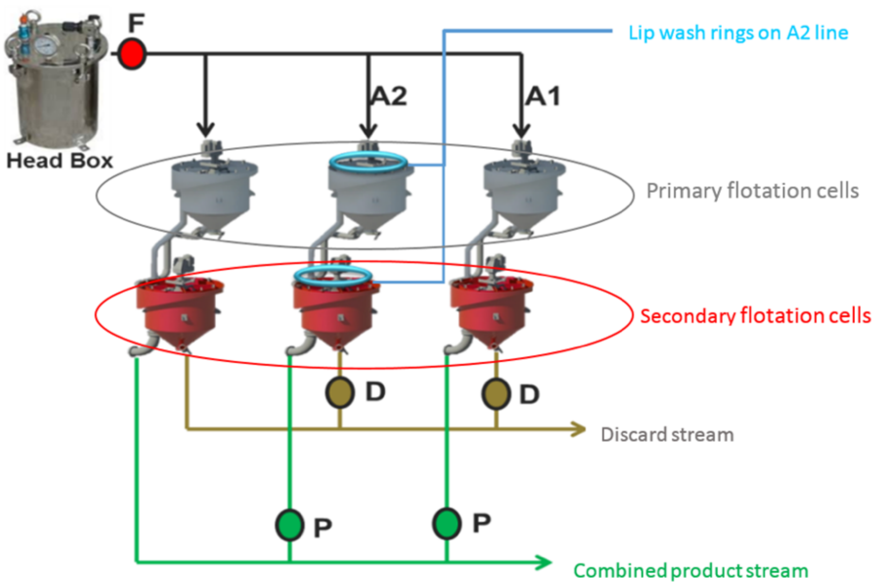

Fig. 3. Schematic of process flow and sampling points for test-work

In an attempt to understand the effects of flotation reagent dosage on the lip washing flotation line, all other parameters were kept constant on both lines.

2.2.2. Plant operation and plant parameters

Mechanical flotation cells known as dual cells are utilised at GHS where conditioned feed slurry, is gravity fed to the flotation cells. The slurry is mixed and dispersed throughout the cell by means of a pump and paddles. In the coal washing process, coal particles with size below 212 μm come from the main dense medium separation (DMS) plant and report to thickeners, and from the thickeners this stream is fed to the flotation module. In the flotation module, the fine coal is pumped into the flotation plant feed tanks where it is diluted with water to achieve the desired feed density of 1.022 ton/m^3. From the feed tank, the slurry is pumped into a head box (F) which serves to distribute the slurry into the three primary flotation cells by gravity. In the primary cells, fast floating coal is recovered as product and the discard slurry is fed to the secondary cells. In the secondary cells, the slow floating coal is recovered as product. The combined product from the primary and secondary cells is pumped to the product filter feed tank and then dewatered using the Ishigaki Lasta filter presses. Tailings from the secondary cells are pumped to the tailings thickener, the underflow from the tailings thickener is dewatered using the Jing Jin filter presses and discarded onto the discard dump. The operation of the flotation plant has been optimised and it is operated at plant parameters shown in Table 1. These plant operating parameters were kept constant in the test-work. These operating plant conditions achieved product qualities of CV of ~27.3 MJ/kg (adb) at average yield of ~54%.

All sampling, preparation of samples and analysis of samples were done in line with International Standards Organisation (ISO) and South African National Standards (SANS) standards (ISO 20904:2006 and SANS 20904:2007). Typical analysis done on the sampling campaign include wet screening for size analysis, ash content and CV analysis. Proximate and ultimate analysis were done on the different feed material used only.

Table 1. Optimal Plant Operating Parameters

Parameter	Value	Unit
Header Box Density	1.022	t/m^3
Feed Slurry Flow Rate	200	m^3/h
Solids tons to Primary cell	12	t/h
Air Flow Rate	51	m^3/h
Superficial Gas Velocity (Jg)	0.98	cm/s
Reagent dosage	1.3	kg reagent/t solids feed
Reagent split (volume) - (Primary: Secondary)	75:25	
Reagent ratio (Collector:Frother)	80:20	
Reagent ratio (CGH7:CGM4)	75:25	

2.2.3. Coal feed characteristics – air dry basis (adb)

Two different coal feeds were used in the test-work (i) High quality coal feed – this is the type of feed blend that is regularly fed to the existing plant during production (ii) Low quality coal feed – this feed is a low yielding coal feed blend which is defined as the coal feed that results in yields that are < 40% in the current flotation plant settings. Low quality coal feed originates from sections in the mine where the floatability characteristics of the coal are less favourable. Table 2 and Table 3 show the Proximate and the Ultimate analysis of the two coal feed types, respectively.

2.2.4. Flotation reagents at GHS

GHS uses flotation reagent(s) called CGH7 and CGM4. CGH7 is a mixture of a hydrocarbon, alcohol and glycol compound groups. This reagent has a 20% frother and 80% collector ratio. Previous tests at GHS have shown that CGH7 operates optimally at this specified ratio. CGH7 is known for its high selectivity of product material over discard material. CGM4 is also a mixture of hydrocarbon, alcohol

Table 2. Proximate analysis

Feed type	Moisture (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)	Total sulphur (%)	CV (MJ/kg)
Higher quality feed	3.2	32.2	19.3	45.2	2.7	21.8
Lower quality feed	3.7	37.7	17.4	41.2	2.4	20.1

Table 3. Ultimate analysis

Feed type	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%) - by diff	Total sulphur (%)
Higher quality feed	73.5	4.3	2.3	17.2	2.7
Lower quality feed	70.5	4.7	2.2	18.8	3.8

and glycol compound groups and is also 20% frother and 80% collector. CGM4 is similar to CGH7 and the only difference is the molecular weight of the glycol component. The exact composition of the reagents (CGH7 and CGM4) are unknown as their formulation is an intellectually property of the supplier. However, it is known that the glycol component of CGM4 has a higher molecular weight compared to that of CGH7. CGM4 therefore has a stronger frother component than CGH7. Various mixtures were investigated to determine which mixture offers the highest yields. The results of these investigations led to the current reagent mix used at GHS plant. The plant is currently dosing the reagents at a ratio of 3:1 (i.e. 75% CGH7 and 25% CGM4).

The aim of installing froth wash at GHS flotation plant was to maximise yield while maintaining product quality. The important question was to understand how much the lip washing technology can increase the yield while maintaining the required product quality. Different sets of test-work were performed to evaluate the impact of lip washing on enhancing fine coal flotation. The test-work conducted evaluated the following: (i) effect of ash content on CV, (ii) effect of varying reagents dosage on the lip wash line, (iii) effect of particle size and (iv) effect of feed coal quality.

The yields presented in the results were calculated from an ash balance, on air dry basis (adb).

2.3. Test-work on product calorific value (CV) and product ash

The coal product after flotation had its CV tested in an adiabatic bomb calorimeter (Peatfield, 2003; Reddick et al., 2007). In addition, proximate analysis was performed to determine the coal ash content (Peatfield, 2003; Reddick et al., 2007). Each test was performed three times to test reproducibility of the data and the mean and standard deviation of the measured parameter recorded. A correlation between the CV and ash content was done using data fitting of the experimental data points. A correlation coefficient (R^2) was determined to evaluate how the data fitted a linear model.

2.4. Test-work on effect of varying reagent dosage on yield and quality using combined PW+SW

The first 4 experimental runs were performed to compare the effect of varying reagent dosage on yield and quality on the A2 line against the yield and quality on A1 (baseline cells) in which the reagent dosages were kept constant. The runs were performed three times and the mean and standard deviation for yield and quality were recorded. The A2 line in runs 1 - 4 applied lip washing on both primary and secondary cells (combined PW + SW) and the A1 was maintained as the baseline flotation cell line that operates under the current plant conditions. Table 4 summarises the reagent dosage for experimental runs 1 - 4. The effect of varying reagent dosage was measured on the basis of ash content and product yield.

2.5. Test-work on the effect of particle size

This test was designed to determine the effect of coal particle size on the yield and quality for flotation

Table 4. Reagent dosages on A1 and A2 lines for Run 1 – 4

Cell Line	Reagent Dosage Rate (kg reagent/ton dry solids fed)			
	Run 1	Run 2	Run 3	Run 4
A1	1.30	1.30	1.30	1.30
A2	1.30	1.45	1.60	1.75

performed at constant reagent dosage of 1.30 kg/t dry solids while applying lip washing on both primary and secondary cells (combined PW + SW) compared to the baseline flotation cell performance (current plant performance). The particle sizes tested were in the range 75 to 500 µm (i.e. 75, 106, 125, 212, 300 and 500 µm). The runs were performed three times and the mean and standard deviation of the objective functions i.e.yield and quality were recorded.

2.6. Test-work on the effect of lip washing on different coal qualities

Two different coal qualities were evaluated (i) High quality coal feed – type of feed blend regularly fed to the plant (ii) Low quality coal feed - Low quality coal feed or low yielding coal blend is defined as the coal feed that results in yields < 40% in the current flotation plant settings. Low quality coal feed originates from sections in the mine where the floatability characteristics of the coal are less favourable. The test runs were performed in triplicates.

Student t-Tests were performed using a null hypothesis that assumes that the two data sets (baseline and lip washing) were likely to have equal population means. A confidence level of 95% for two tailed test was used.

3. Results and discussion

3.1. Product calorific value (CV) and product ash content correlation

Fig. 4 shows a plot of the product CV against the product ash content on air dry basis (adb) for different product samples taken during the test-work. The results in Fig. 4 show that the coal product CV is inversely proportional to the coal product ash content. The equation for this correlation is:

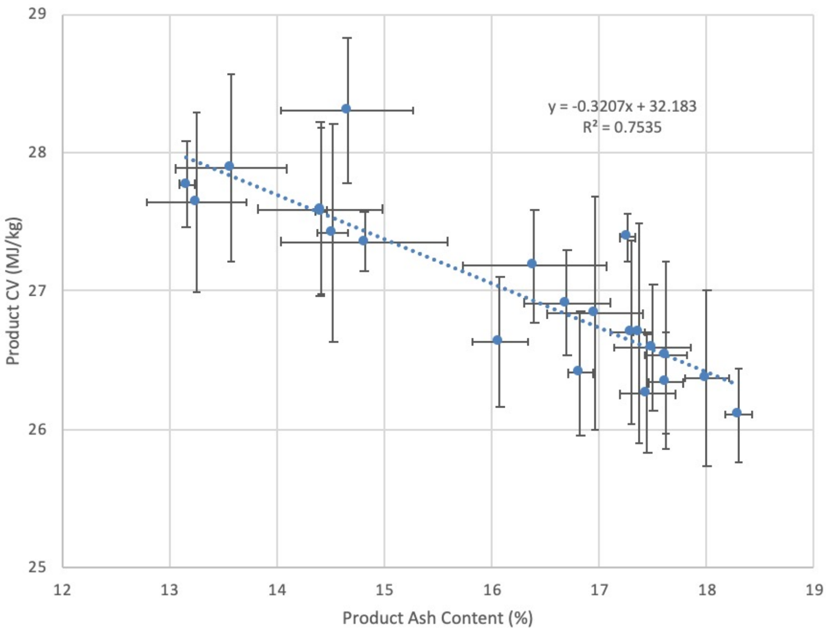

Fig. 4. Coal CV against ash content on air dry basis

$$Product\ CV\ (MJ/kg) = -0.3158\ Product\ Ash\ Content\ (\%) + 32.112. \quad (1)$$

It confirms that there is a correlation between product CV and product ash content which is a well-known fact in coal processing industry.

In the following tests, the criteria for achieving acceptable coal qualities via the lip washing route is met when the lip washing product ash content is similar to the baseline product ash content for the same coal feed type.

3.2 Effect of varying reagent dosage on yield and quality while applying lip washing on primary and secondary flotation cells

Fig. 5 shows the yield achieved in each of the first 4 flotation test runs (1–4) in which flotation was performed on the feed having an average ash content of 32.32% at reagent dosage of 1.30 kg/t for the baseline cells and at increasing dosage for the lip washing cells.

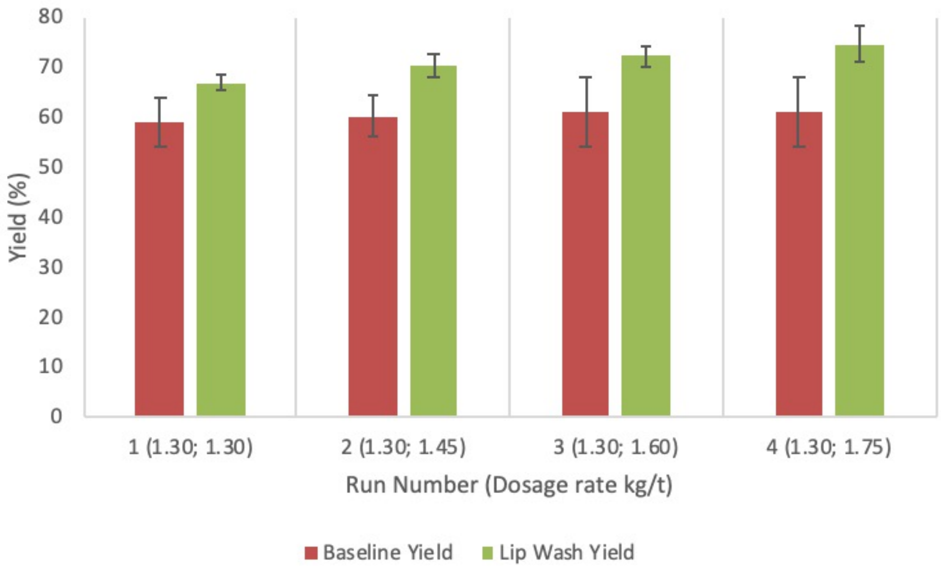

Fig. 5. Effect of lip washing and reagent dosage on product yield for Runs 1-4

The results for flotation at the common reagent dosage of 1.30 kg/t on both baseline cells and lip wash cells clearly demonstrate that an increase in yield occurs when lip washing is utilised, the yield without lip washing was ~59% and yield with lip washing increased to ~67%, which is almost a 10% jump in yield. Runs 2 – 4 were conducted at higher dosages on the lip washing line only and the results demonstrate that the yield increases as reagent dosage increases. The yield is ~67% at reagent dosage of 1.3 kg/t and ~74% at reagent dosage of 1.75 kg/t. It could therefore be inferred that lip washing has a positive effect of improving the yield on coal fines flotation and that the increase in the reagent dosage further increases the yield. This increase in yield as the reagent dosage increases was also observed by Huang et al. (2019). However, it was observed that the increase in the yield with reagent dosages is plateauing off as dosage increases. This is likely as a result of the unavailability of the target mineral surfaces to which the reagent should adsorb at higher reagent dosages, hence the increase in reagent dosage does not cause an expected corresponding increase in the uptake of the target minerals. Therefore, an optimum reagent dosage should be determined to avoid wastage of the reagents. Flotation reagent costs are a major operational cost driver in the flotation process and therefore should be optimised.

The optimum reagent dosage should also be the dosage that produces product quality (or product ash) from lip washing cells that is comparable to that achieved with baseline cells. If the increased yields obtained by lip washing are not accompanied by a product ash similar to the baseline cells, lip washing will not be a viable option for the plant as product quality would be compromised in achieving the increased yield.

Student t-Tests were performed on the data using an α of 5% for two tailed test for data in Fig. 5. The t-test done was two-sample assuming unequal variance for baseline and lip wash Yield and Ash content and the differences were found to be insignificant.

Fig. 6 shows a plot of yield for the baseline and the lip washing flotation line and the corresponding product ash content from the products obtained in both baseline flotation and lip washing flotation.

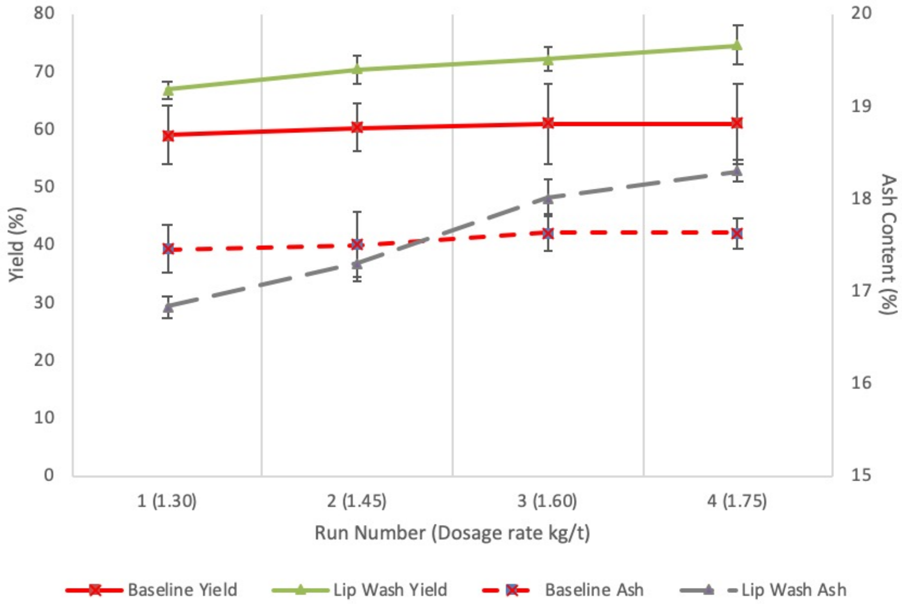

Fig. 6. Product quality and Yield for runs 1-4

The results demonstrate that the product quality produced from lip washing flotation at reagent dosages of 1.30 and 1.45 kg/t is better than that obtained from baseline flotation i.e. (runs 1 - 2). When the reagent dosage is increased to 1.6 (run 3) and then 1.75 kg/t (run 4), the ash content of the lip washing product increases above that of the baseline product indicating that the resultant product quality has become poorer. The results suggest that in order to realise improved yields and still obtain product quality comparable or better than that achieved using the conventional baseline flotation, reagent dosage of 1.45 kg/t or 1.30 kg/t needs to be used. At higher reagent dosages (1.60 – 1.75 kg/t), the lip washing does not appear to clean the froth sufficiently. The reason could be that at higher reagent dosages a higher bubble surface area flux occurs as a result of an increased frother effect. This causes an increase in the degree of particle entrainment in the water associated with the froth resulting in an elevated uptake of gangue or ash particles which lowers the product quality, this was also observed by Huang et al. (2019); Kumar and Kumar, (2018) and Wang et al., 2017.

Fig. 7 shows that the CVs of coal products obtained by lip washing are generally in the same range to CVs of coal products obtained from flotation without lip washing. It is also observed for lip washing, where the product ash varies significantly, that the lower the product ash the higher the product CV and when the product ash is high, the CV is low as expected. The product CVs achieved with lip washing further proves that lip washing can produce a product with qualities comparable to that produced by conventional plant cell configuration but at higher product yields.

3.2 Yield and quality as a function of particle size

Fig. 8 shows a plot of the yield and product ash content for flotation done on separate size fractions at reagent dosage of 1.30 kg/t for both baseline flotation and lip washing flotation.

Yield generally increases as particle size increases from 75 to 300 µm and then decreases as the particle size increases from 300 to 500 µm for both baseline flotation and lip washing flotation. The ash content in the product is shown to decrease with an increase in particle size. This suggests that when different size classes are floated separately finer particle flotation products retain higher amounts of ash than larger particle fractions. This is due to higher entrainment of ash/gangue associated with flotation of finer material. The plot also shows that flotation of particles in the size class -500 + 300 µm, does not result in an appreciable yield increase when lip washing flotation is used. However, as particles get finer (smaller) i.e. < 300 µm, lip washing flotation causes a significant increase in the yield of the respective particle sizes. The ash content, however, appears to be comparable across the entire particle size spectrum for both baseline flotation and lip washing flotation products, meaning that quality is maintained while product yield is being increased. It can also be inferred that as long as the flotation plant does not receive oversized materials (>300 µm), lip washing will produce higher yields and still meet required product quality when reagent dosage of 1.30 kg/t is used.

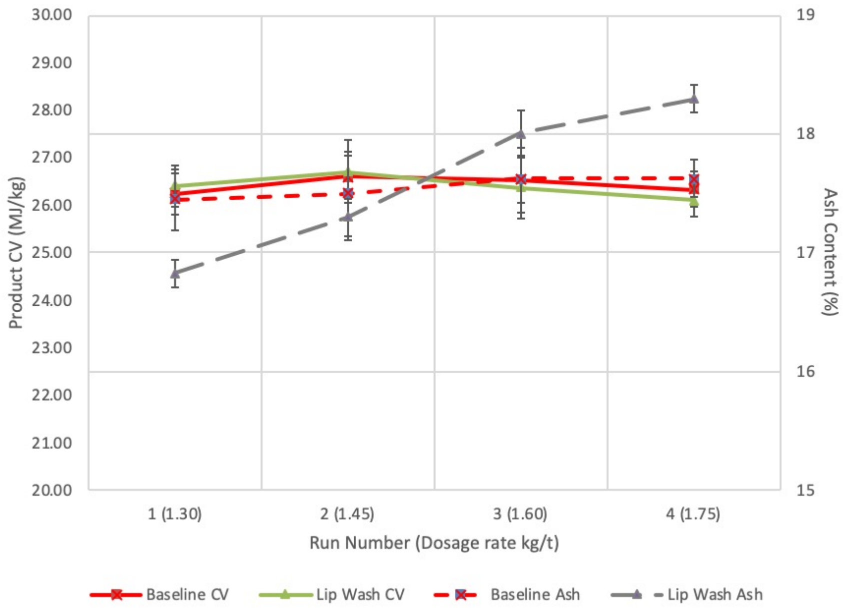

Fig. 7. Product CV and Ash Content for runs 1-4

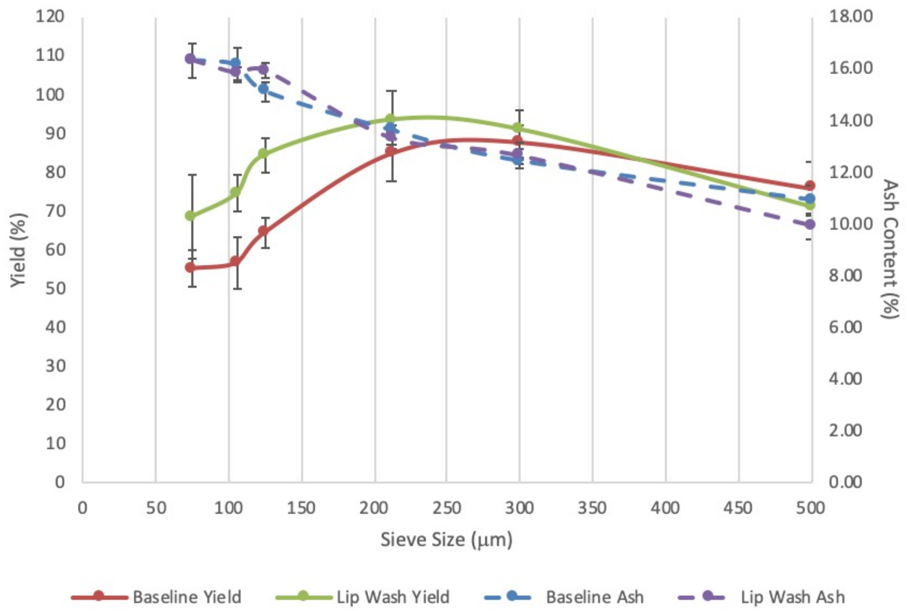

Fig. 8. Yield and product quality versus particle size

Nkolele (2004) made similar observations and attributed this to the difference in the properties of coal surfaces between the size classes i.e. between fine coal particles (< 500 µm) and ultra-fine coal particles (< 100 µm). Laskowski et al. (2007), and Gupta and Yan (2016) established that the optimum size range of coal particles that showed best floatability was around < 350 µm which is a similar range to what was observed in the current studies. Kumar and Kumar (2018) highlighted that flotation is dependent on the particle size and that when particles > 500 µm, they will not remain attached to air bubbles for long while finer particles will have less air bubble–particle interaction thereby reducing their capture and yield. They indicated that the optimum particle size range for coal flotation was between 300 and 106 µm which is consistent with observations made in these studies.

The reason why higher yields are recorded as the particle size becomes smaller (finer) i.e. < 300 µm is that gangue particles are successfully separated from the coal particles as seen in Fig. 9 (Wang and Li, 2020; Wills and Napier-Munn, 2006). Liberated particles tend to yield better during flotation and this explains why yield drastically drops for particles >300 µm where particles are likely to be partially liberated.

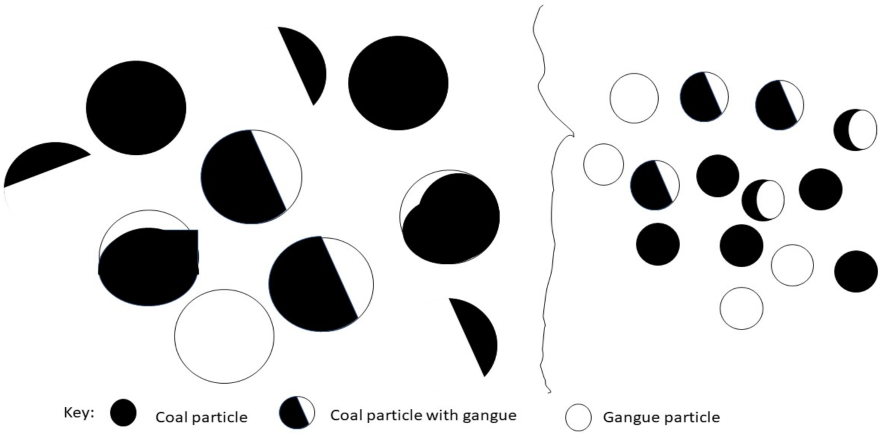

Fig. 9. Size reduction liberating wanted material (Adapted from Nkolele, 2004; Wills and Napier-Munn, 2006)

On the other hand, as particle sizes become much finer there is an increase in unwanted entrainment of gangue particles to the concentrate which increases the ash content of the froth and reduces the quality. The recovery or yield of coal particles is also reduced as particles get smaller because the froth easily drains off the smaller particles that do not attach firmly to bubbles (Wang and Li, 2020).

3.4. Effect of lip washing on different coal quality

Fig. 10 shows the yield and qualities obtained when high and low quality coal feeds were floated at reagent dosage of 1.60 kg/t. Low quality coal feed is defined as the feed that has ash content above 36% and achieves yields that are lower than 40% under baseline flotation conditions.

The results show that an increase in yield is observed when lip washing is applied to both high quality and low quality coal feeds. The indication is that a much bigger increase in the yield was achievable with lip washing of low quality coal feed. The yield differential for the low quality feed was

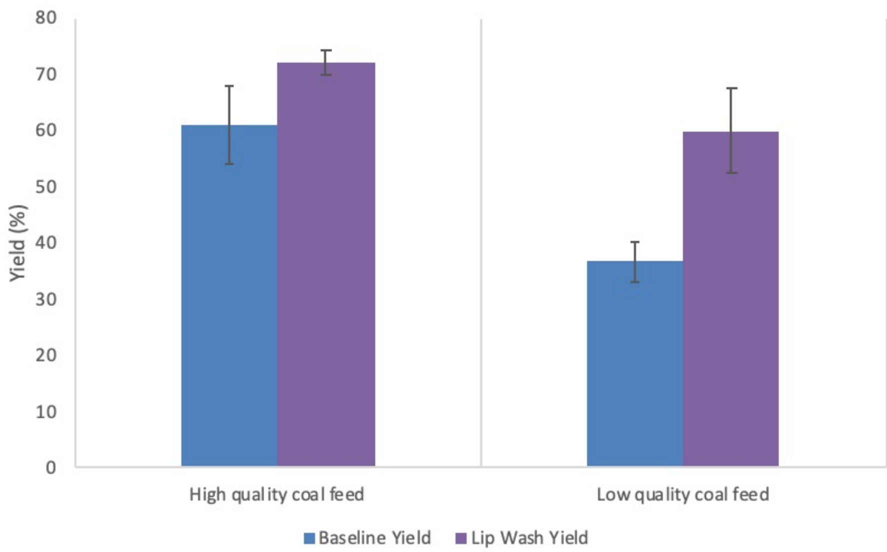

Fig. 10. Effect of lip washing on high and low quality coal feeds at 1.60 kg/t reagent dosage

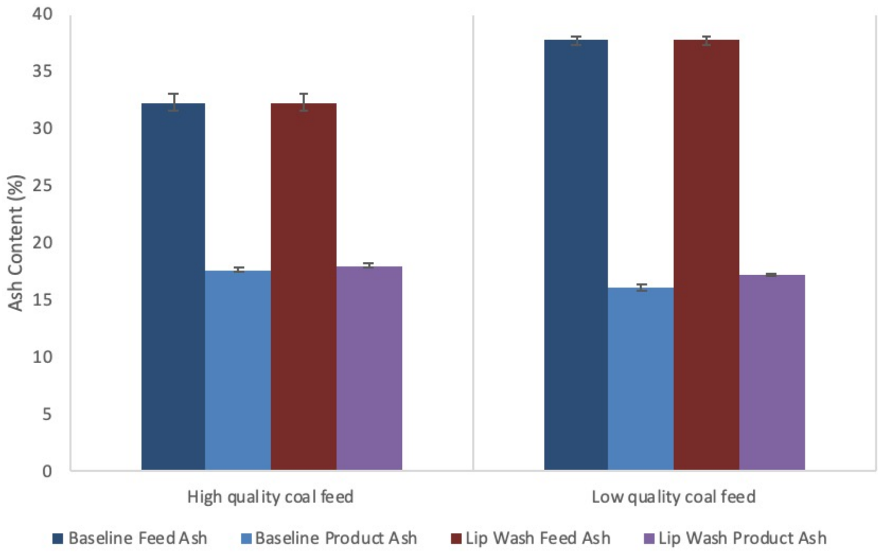

Fig. 11. Ash content of high quality coal feed and low quality coal feed before and after washing at 1.60 kg/t reagent dosage

Δ 23.32% compared to 7.92% for the high quality coal feed.

Fig. 11 shows that the ash content of the lower quality coal (37.70%) is clearly higher than that of good quality coal (32.30%) as expected. The ash content after lip washing of good quality coal is 18% which is comparable to the quality obtained from baseline washing of the same coal which is 17.62%. The ash content after lip washing of poor quality coal is 17.27%which is marginally higher than that for baseline washing of the same coal which is 16.08%, both are however in the range of what was achievable when washing good quality coal. This suggests that poor quality coal feeds can be floated as effectively as good quality coal to produce a product of acceptable quality. The superior yield gain when poor coal feed is floated with lip washing further reinforces the need to introduce a lip washing system at GHS as it can help realise substantial gains in the event that the coal feed quality from the mines drops drastically. The value of lip washing will become more significant as high quality coal reserves get depleted and lower quality coal deposits need to be mined and beneficiated to extend the life of the mine.

4. Conclusions

Most froth washing applications reported in literature show that froth washing generally increases the product quality (by decreasing product ash content) while yield normally decreases (Laskowski et al., 2007; Huang et al., 2019). However, the results in this present work indicate that it is possible that a yield increase can occur while product quality is improved or maintained by lip washing. This research has enabled a better understanding of the dynamics and the influence of a lip washing system on the dual flotation cells at GHS flotation plant. The test-work done in the study has shown that increases in coal yield of between 10 and 25% are possible when lip washing is applied to the current configuration of flotation cells at GHS, while maintaining a product quality similar or better than that produced from baseline cells if reagent dosage on lip washing cells is between 1.30 and 1.45 kg/t. Higher reagent dosages of 1.60 and 1.75 kg/t improves the yield marginally but result in a decrease in product quality which is undesirable. When different coal particle size fractions were floated separately the yield generally increased as particle size increases from 75 to 300 µm and then decreases as the particle size increases from 300 to 500 µm for both baseline flotation and lip washing flotation. As particles get finer (smaller) i.e. < 300 µm, lip washing flotation caused a significant increase in the yield of the respective particle sizes. The optimum size class for flotation was found to be between 212 and 300 µm. The test-work has also shown that, when lip washing is used, higher yields and the required qualities are possible if the coal feed introduced to the flotation units is of low or poor quality. Therefore, lip washing increases the range of coal feeds that can be efficiently processed in the coal flotation plant.

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