COALTECH 2020

Beneficiation of Fine Coal: Froth Flotation Efficiency

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TABLE OF CONTENTS

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1. INTRODUCTION

Froth flotation has been used extensively in the past to beneficiate fine coal (nominal minus 0,5 mm) in Natal, as well as at Grootegeluk in the Waterberg coalfield. In most of these cases, the fine coal produced from the froth flotation plants was destined for use as either a coking coal or a blend-coking coal.

One of the last flotation plants in Natal closed down recently when Durnacol Colliery ceased operations.

The only froth flotation plant currently processing fine coal (nominally minus 2 mm in this case) is the one at Tsikondeni Colliery, where a coking coal is produced.

The efficiency of this plant was determined from samples of feed, product and tailings provided by the mine so as to be able to compare the efficiency with that of spirals.

The process was not used in the Witbank/Middelburg area since the coal from this region was generally considered “non-floating”.

When spirals were introduced in the early 1980s, the fine coal that would normally have been subjected to froth flotation was sent to the more economical spirals at plants such as Grootegeluk. The ultra-fine coal, which cannot be beneficiated by spirals, became the new feed to froth flotation plants.

From about 1985, starting at the now-closed Landau III plant[1], a number of experiments were conducted to evaluate the potential of froth flotation for the beneficiation of Witbank-type ultra-fine coal. These experiments showed, right from the start, that the process was technically viable and that good yields and acceptable quality of coal could be obtained from the ultra-fine fraction. However, the amount of collector required to float the coal was higher than that traditionally required in Natal, which made the process relatively expensive.

At present, froth flotation is the only viable processing option for ultra-fine coal and a number of pilot- and full-scale plants have been commissioned in the Witbank/Middelburg area.

Alternative, gravity-based methods such as the Mozley Multi-Gravity Separator[2], are being investigated for processing the ultra-fine fraction. To date, these methods have not yet been sufficiently proven for them to replace froth flotation.

One of the aspects regarding the flotation of ultra-fine coal that has not been conclusively demonstrated is the choice of flotation unit to be employed.

Although a number of flotation machines are used around the world, and each claims to be the best, no definite answer is known. In South Africa, the column-type cell has gained some popularity. The early tests were carried out using pilot-scale conventional Denver cells and proved very successful. Anglo Coal also recently developed their own patented type of froth cell.

The opinion has been expressed that column cells are very effective in recovering the finer part of the ultra-fine coal, but are not very good at recovering the coarser part of the coal. Conventional, sub-aeration cells, on the other hand, are thought to recover the coarser coal better.

As part of this project, it was deemed necessary to carry out a brief investigation into froth flotation to attempt to obtain some idea of the effectiveness of column-type cells as opposed to conventional cells.

Fortunately Ingwe Coal also felt the same need and decided to install both column-type cells and conventional tank cells at Koornfontein Colliery. The personnel at Koornfontein are currently investigating the comparative merits of the two types of flotation cells in great detail.

Although this report contains some results obtained with samples from the Koornfontein column cell, only a very cursory investigation could be done. A much more thorough evaluation is being carried out by Ingwe.

A second issue regarding froth flotation, especially that of ultra-fine coal, is whether or not it would be economically viable to ‘de-slime’ the feed to the cells.

Ultra-fine coal has a very large surface area per unit mass, approximately 53 000 m^2/ton. During flotation, the surface of the coal particles needs to be coated with a collector and since the surface area is so large, a large amount of collector is theoretically required.

The large surface area also implies that the fine coal will retain a large amount of water and the larger the surface area, the more difficult it is to dewater the coal.

If the minus 25 micron size fraction can be removed from the minus 150 micron coal fed to the flotation cells, a large reduction in surface area will be achieved. It is thought that this may reduce the amount of collector required and also assist in dewatering the froth product.

A very brief evaluation of the viability of de-sliming the flotation feed at 25 micron was carried out.

2. METHODOLOGY

Samples of the feed to cells as well as of the froth product and the tailings were obtained from Tsikondeni Mine. The samples were taken by the mine and transported to Pretoria in sealed containers.

After being dried and weighed, the samples were screened to establish their size consist. The plus 100 micron size fractions were recombined and subjected to float-and-sink analysis so as to enable a partition curve of the separation effected by froth flotation on the minus 2 mm, plus 100 micron size fraction to be derived.

The minus 106 micron size fractions were wet-screened into smaller size fractions. The ash content of each size fraction was determined to allow the yield per size fraction to be established by the ash-balance method.

In addition, a set of samples representing the feed, froth product and tailings was obtained from the Koornfontein column cell. These samples were also wet-screened into a number of size fractions and the ash content of each size fraction was determined.

Flotation feed samples were supplied by Kleinkopje and Koornfontein Collieries.

These samples were divided into two portions each and a series of laboratory-scale froth flotation tests was carried out on one portion of each sample. In these tests, the amount of collector added to the pulp during conditioning of the sample was varied over a range of values to yield a corresponding range of product yields and qualities. The ash content of the feed, as well as of each product and tailing was determined.

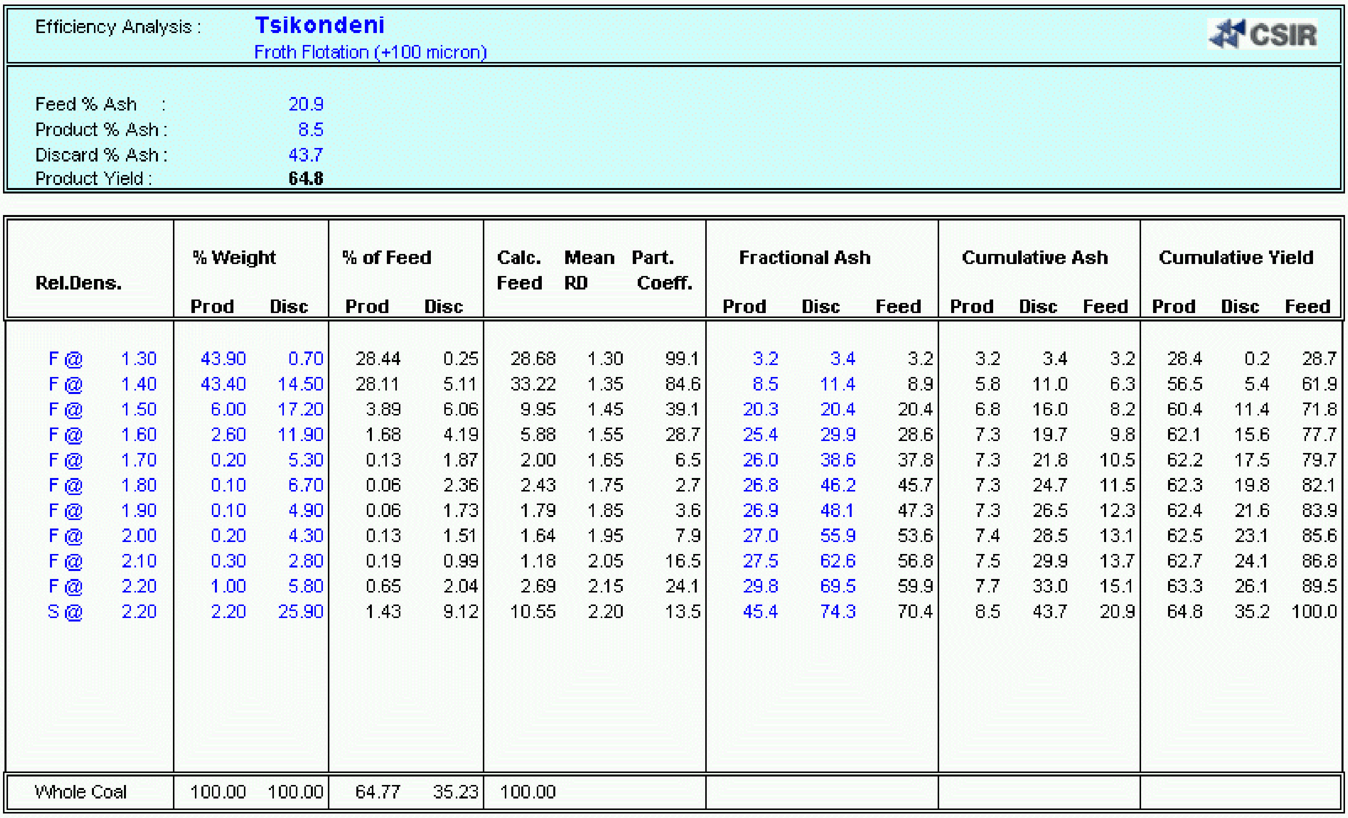
The second portion of each sample was de-slimed at 25 micron and the flotation tests were repeated using the de-slimed plus 25 micron samples.

All laboratory work was conducted by the SABS-CET laboratory.

3. RESULTS OBTAINED

The efficiency of the froth flotation plant at Tsikondeni, as determined from the samples supplied by the mine, is shown in Tables 1 and 2. The partition curve is shown in Figure 1.

Table 1: Efficiency calculations



Efficiency Analysis : **Tsikondeni**
Froth Flotation (+100 micron)

Feed % Ash : 20.9
Product % Ash : 8.5
Discard % Ash : 43.7
Product Yield : **64.8**

Rel.Dens.	% Weight		% of Feed		Calc. Feed	Mean RD	Part. Coeff.	Fractional Ash			Cumulative Ash			Cumulative Yield		
	Prod	Disc	Prod	Disc				Prod	Disc	Feed	Prod	Disc	Feed	Prod	Disc	Feed
F @ 1.30	43.90	0.70	28.44	0.25	28.68	1.30	99.1	3.2	3.4	3.2	3.2	3.4	3.2	28.4	0.2	28.7
F @ 1.40	43.40	14.50	28.11	5.11	33.22	1.35	84.6	8.5	11.4	8.9	5.8	11.0	6.3	56.5	5.4	61.9
F @ 1.50	6.00	17.20	3.89	6.06	9.95	1.45	39.1	20.3	20.4	20.4	6.8	16.0	8.2	60.4	11.4	71.8
F @ 1.60	2.60	11.90	1.68	4.19	5.88	1.55	28.7	25.4	29.9	28.6	7.3	19.7	9.8	62.1	15.6	77.7
F @ 1.70	0.20	5.30	0.13	1.87	2.00	1.65	6.5	26.0	38.6	37.8	7.3	21.8	10.5	62.2	17.5	79.7
F @ 1.80	0.10	6.70	0.06	2.36	2.43	1.75	2.7	26.8	46.2	45.7	7.3	24.7	11.5	62.3	19.8	82.1
F @ 1.90	0.10	4.90	0.06	1.73	1.79	1.85	3.6	26.9	48.1	47.3	7.3	26.5	12.3	62.4	21.6	83.9
F @ 2.00	0.20	4.30	0.13	1.51	1.64	1.95	7.9	27.0	55.9	53.6	7.4	28.5	13.1	62.5	23.1	85.6
F @ 2.10	0.30	2.80	0.19	0.99	1.18	2.05	16.5	27.5	62.6	56.8	7.5	29.9	13.7	62.7	24.1	86.8
F @ 2.20	1.00	5.80	0.65	2.04	2.69	2.15	24.1	29.8	69.5	59.9	7.7	33.0	15.1	63.3	26.1	89.5
S @ 2.20	2.20	25.90	1.43	9.12	10.55	2.20	13.5	45.4	74.3	70.4	8.5	43.7	20.9	64.8	35.2	100.0
Whole Coal	100.00	100.00	64.77	35.23	100.00											

Table 2: Efficiency results

Efficiency Test Results

Tsikondeni
Froth Flotation (+100 micron)

Feed % Ash	20.9
Product % Ash	8.5
Discard % Ash	43.7
Product Yield	64.8
D50	1.4265
Ep	0.0568
Org Eff	88.8
Sink in Float	5.35
Float in Sink	6.95
Total Misplaced	12.29

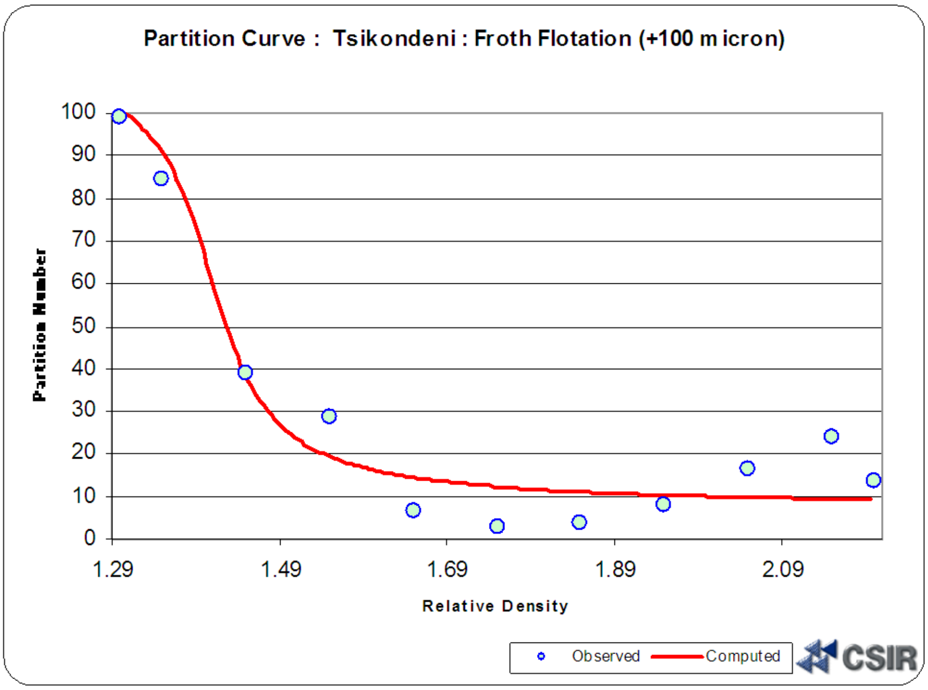


Figure 1: Partition curve

The results obtained on the minus 100 micron coal samples from Tsikondeni and the Koornfontein column cell are shown in Tables 3 and 4.

Table 3: Results obtained on Tsikondeni ultra-fine coal

	Feed to Flotation cells					
Screen size	Frac.	Moisture	Ash	Cum.	Moisture	Ash
microns	Yield, %	%	%	Yield, %	%	%
+75	20.1	0.9	22.8	20.1	0.9	22.8
-75 x 45	25.4	0.9	26.8	45.5	0.9	25.0
-45 x 25	12.8	1.0	27.7	58.3	0.9	25.6
-25	41.7	1.2	40.8	100.0	1.0	31.9

	Flotation Product					
Screen size	Frac.	Moisture	Ash	Cum.	Moisture	Ash
microns	Yield, %	%	%	Yield, %	%	%
+75	21.4	1.0	11.8	21.4	1.0	11.8
-75 x 45	21.8	1.0	13.4	43.2	1.0	12.6
-45 x 25	17.9	1.1	15.0	61.1	1.0	13.3
-25	38.9	1.2	25.3	100.0	1.1	18.0

	Flotation Tails					
Screen size	Frac.	Moisture	Ash	Cum.	Moisture	Ash
microns	Yield, %	%	%	Yield, %	%	%
+75	7.7	0.8	60.4	7.7	0.8	60.4
-75 x 45	17.5	0.7	63.0	25.1	0.7	62.2
-45 x 25	17.6	0.6	65.8	42.8	0.7	63.7
-25	57.2	1.3	70.7	100.0	1.0	67.7

Table 4: Results obtained on Koornfontein ultra-fine coal

	Feed to Flotation cells					
Screen size	Frac.	Moisture	Ash	Cum.	Moisture	Ash
microns	Yield, %	%	%	Yield, %	%	%
-200+150	0.5	3.4	6.9	0.5	3.40	6.90
-150+75	8.0	1.8	9.4	8.5	1.89	9.25
-75 + 45	14.0	1.7	12.0	22.5	1.77	10.96
-45 + 25	10.0	1.5	14.4	32.5	1.69	12.02
-25	67.5	2.5	21.5	100	2.24	18.42

	Flotation Product					
Screen size	Frac.	Moisture	Ash	Cum.	Moisture	Ash
microns	Yield, %	%	%	Yield, %	%	%
-200+150	3.2	3.1	6.5	3.2	3.10	6.50
-150+75	14.7	2.1	8.5	17.9	2.28	8.14
-75 + 45	17.7	2.7	11.6	35.6	2.49	9.86
-45 + 25	9.4	3.2	13.2	45	2.64	10.56
-25	55.0	3	14.6	100	2.84	12.78

	Flotation Tails					
Screen size	Frac.	Moisture	Ash	Cum.	Moisture	Ash
microns	Yield, %	%	%	Yield, %	%	%
-200+150	2.2	3.10	9.20	2.2	3.10	9.20
-150+75	13.2	2.1	10.8	15.4	2.24	10.57
-75 + 45	13.3	2.7	16.3	28.7	2.45	13.23
-45 + 25	14.3	3.2	26.2	43	2.70	17.54
-25	57.0	3	46	100	2.87	33.76

The results of the flotation tests conducted in order to establish the effect of de-sliming the feed to the flotation cells are shown in Tables 5 and 6.

Table 5: Results of Koornfontein flotation tests

Un-deslimed samples

Reagent	Concentrate	Tailing	Total	% conc	% ash	% ash
L/ton	Mass/g	Mass/g	Mass/g		conc	tail
0.25	36.02	265.95	301.97	11.9	19.3	20.6
0.50	47.40	250.62	298.02	15.9	18.4	21.0
1.00	74.08	213.34	287.42	25.8	14.0	23.3
1.50	107.74	183.02	290.76	37.1	13.6	24.7
2.00	173.09	117.38	290.47	59.6	15.3	29.9

De-slimed samples

Reagent	Concentrate	Tailing	Total	% conc	% ash	% ash	Net Yield
L/ton	Mass/g	Mass/g	Mass/g		conc	tail	
0.25	24.81	275.83	300.64	8.3	12.9	14.8	3.3
0.50	37.05	263.04	300.09	12.3	11.3	15.6	4.9
1.00	200.77	99.96	300.73	66.8	12.4	16.5	26.7
1.50	237.03	57.34	294.37	80.5	12.8	24.5	32.2
2.00	267.69	27.18	294.87	90.8	13.6	32.1	36.3

Table 6: Results of Kleinkopje flotation tests

Un-deslimed samples

Reagent	Concentrate	Tailing	Total	% conc	% ash	% ash
L/ton	Mass/g	Mass/g	Mass/g		conc	tail
0.25	11.28	282.74	294.02	3.8	17.0	20.6
0.50	27.00	268.13	295.13	9.1	15.5	21.0
1.00	71.52	225.29	296.81	24.1	14.7	23.3
1.50	126.11	173.13	299.24	42.1	16.3	24.7
2.00	165.50	130.81	296.31	55.9	17.9	29.9

De-slimed samples

Reagent	Concentrate	Tailing	Total	% conc	% ash	% ash	Net Yield
L/ton	Mass/g	Mass/g	Mass/g		conc	tail	
0.25	17.08	280.58	297.66	5.7	15.7	21.5	3.4
0.50	31.98	266.71	298.69	10.7	12.3	22.4	6.4
1.00	151.95	144.63	296.58	51.2	17.0	26.7	30.7
1.50	194.28	101.82	296.10	65.6	18.3	28.3	39.4
2.00	223.96	68.47	292.43	76.6	18.6	30.8	46.0

4. DISCUSSION

4.1 Efficiency of Tsikondeni flotation plant

The efficiency data obtained from the Tsikondeni samples show that the separation achieved on the -2 + 0,1 mm size fraction is quite good. The EP value of 0,057 Is better than that obtainable from a spiral. It is also interesting to note that a relatively low cut-point relative density of 1,427 has been achieved.

The partition curve exhibits a marked ‘tail’. The Erasmus curve-fitting routine employed to plot the partition curve cannot readily accommodate this, as can be seen from Figure 1.

Figure 2 shows the partition curve obtained comparison with the curve for a spiral. As can be seen from the figure, the flotation separation is sharper than that of the spiral.

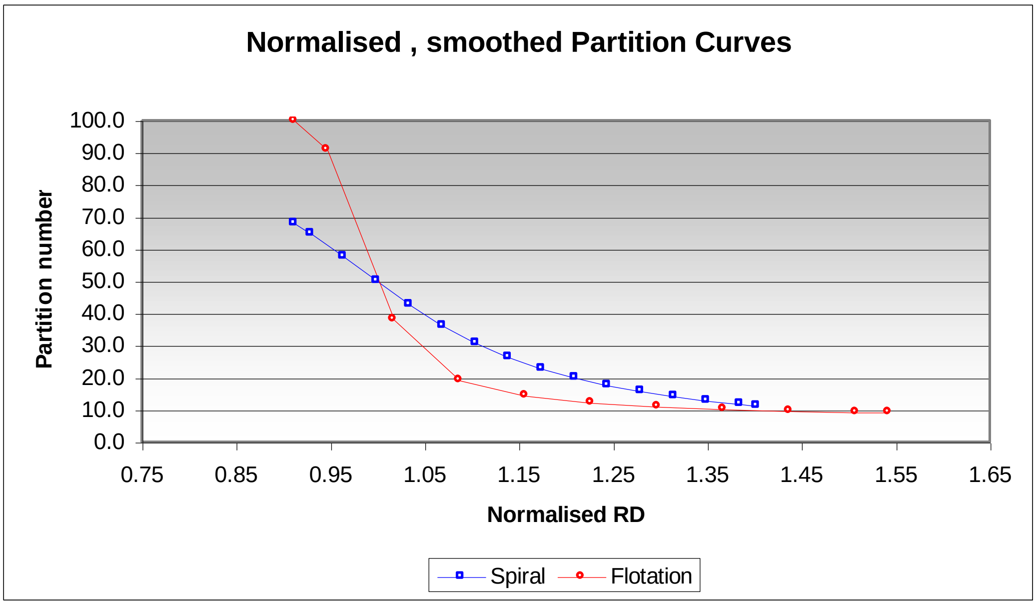


Figure 2:Flotation and spiral partition curves compared

4.2 Efficiency of ultra-fine coal flotation

The data obtained from the Tsikondeni minus 100 micron size fractions are shown in Figures 3, 4 and 5.

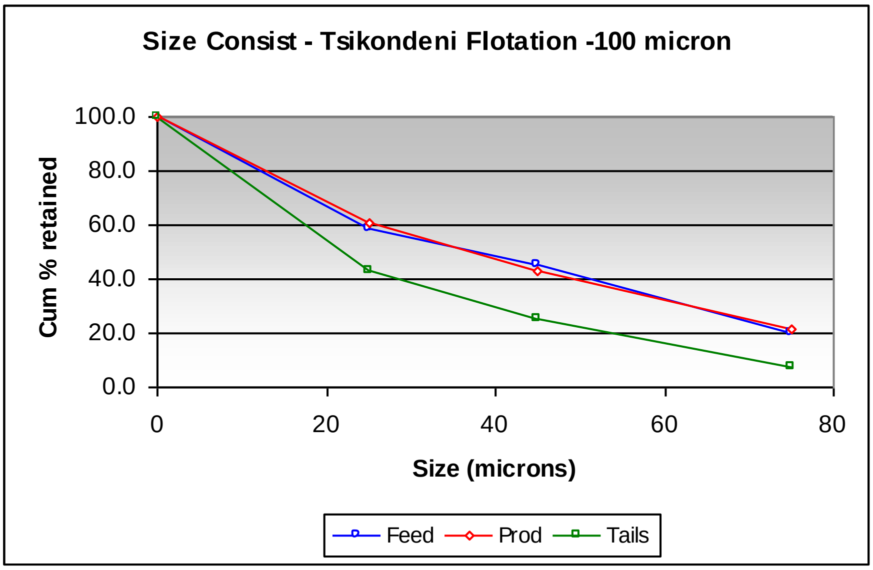


Figure 3: Size consist of Tsikondeni -100 micron samples

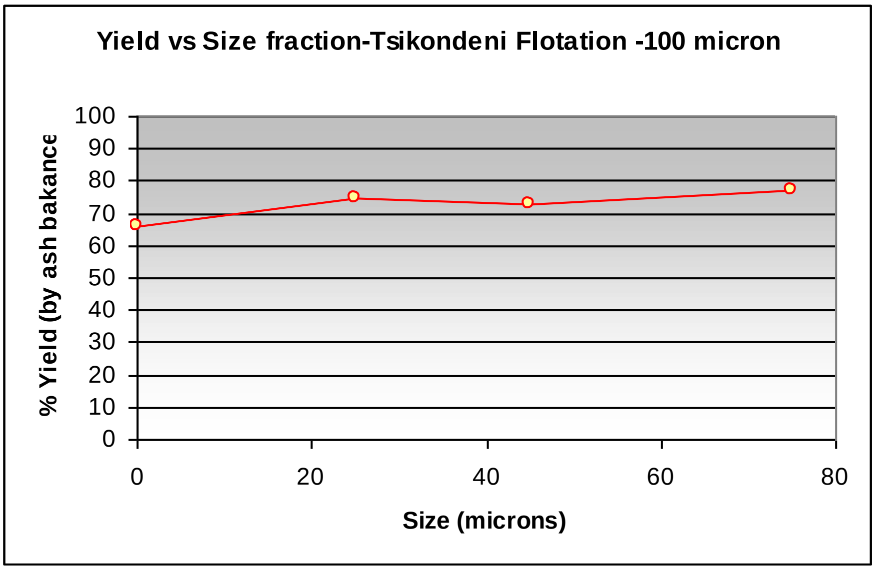


Figure 4: Yield by size fraction for Tsikondeni -100 micron coal

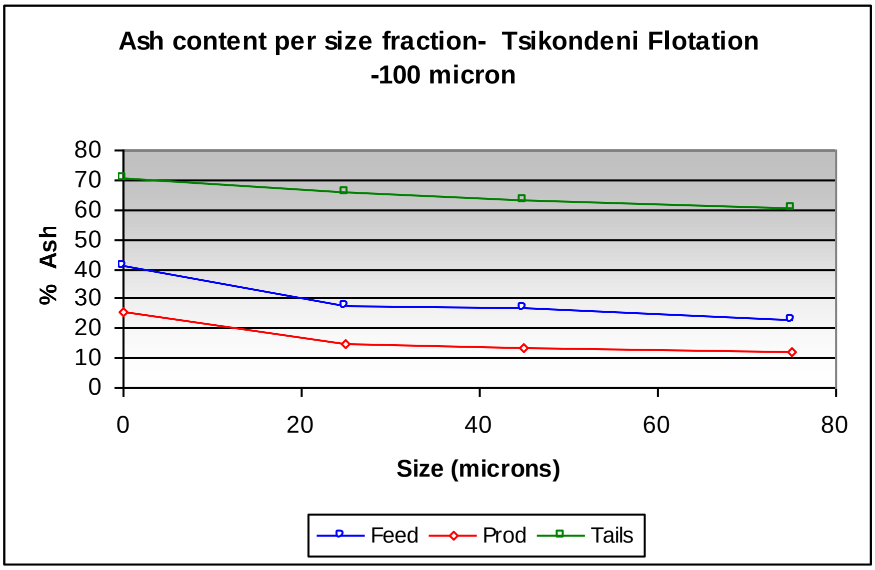


Figure 5: Ash content per size fraction for Tsikondeni -100 micron coal

From the above three figures, it can be seen that the discard fraction is finer than both the feed and product fractions.

The yield, calculated by ash balance, is not markedly different for the different size fractions. The finest fraction has the highest feed ash and also the highest product and tailings ash.

The overall recovery for this size fraction is 71,9 % and the product ash content is 18 %. The tailings ash content is 67,7 %.

The data obtained from the Koornfontein minus 150 micron coal samples are shown in Figures 6, 7 and 8.

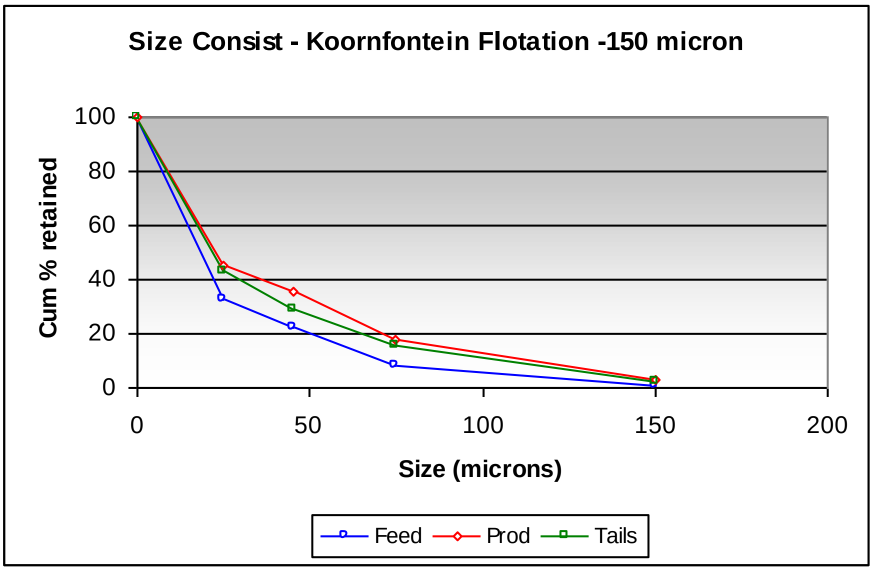


Figure 6: Size consist of Koornfontein -150 micron coal

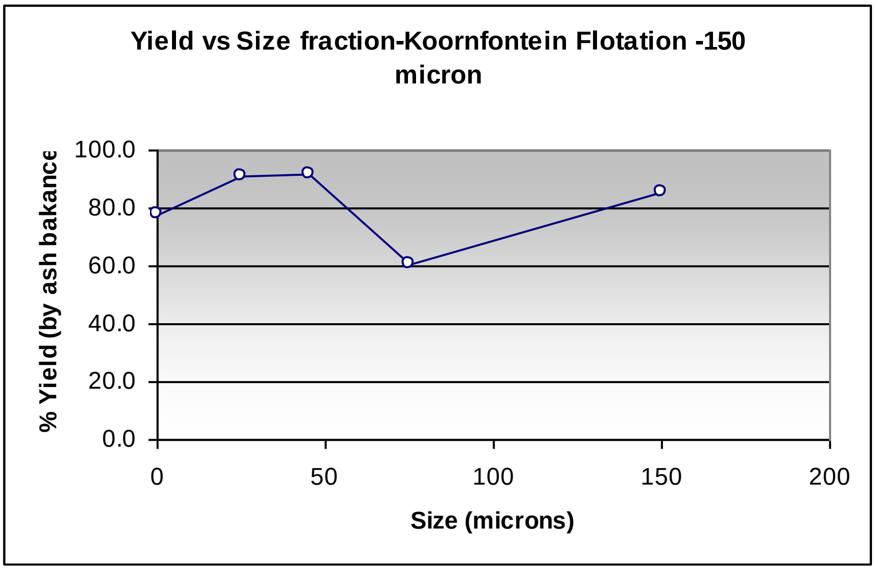


Figure 7: Yield by size fraction for Koornfontein -150 micron coal

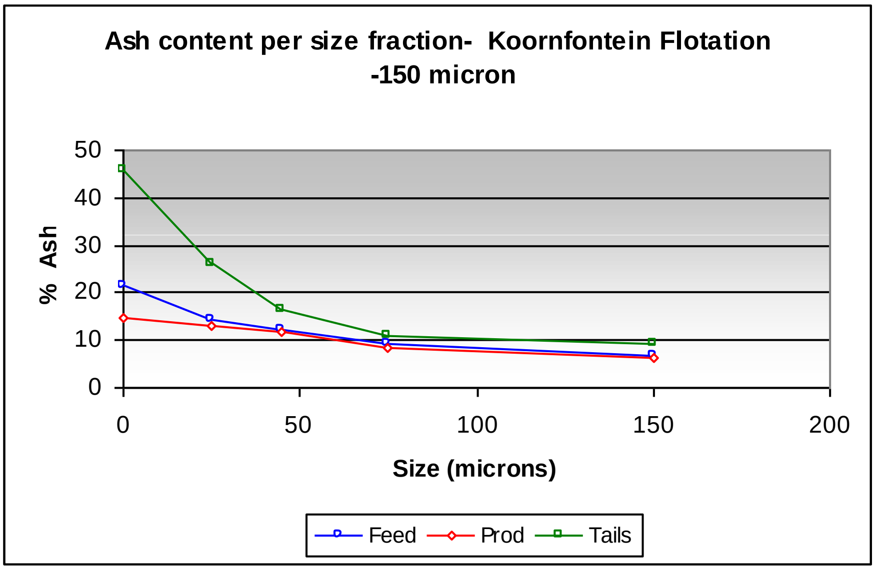


Figure 8: Ash content per size fraction for Koornfontein -150 micron coal

From Figure 6, it can be seen that there are no big differences in size consist between the feed, product and tailing samples although the product is coarsest and the feed finest of the three samples.

As in the case of the Tsikondeni coal, the yield per size fraction, determined by ash-balance, does not vary significantly with particle size.

The overall yield achieved is 73,1 %, with a product ash content of 12,8 % and a tailings ash content of 33,8 %.

The results show that the coarser size fractions of the feed, the product and the discard samples all have low ash contents. There is also very little difference between the ash contents of the three samples in the coarser size ranges. In the finer size ranges, the difference in ash contents is much more marked.

The following graph, Figure 9, depicts the “upgrade ratio”, defined as the feed ash content per size fraction divided by the product ash content per size fraction, for both the Koornfontein and Tsikondeni samples.

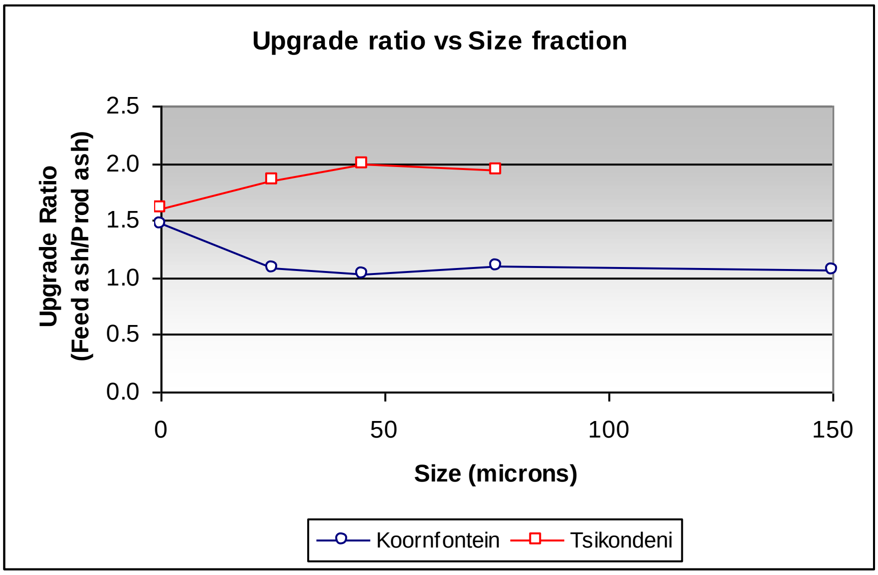


Figure 9: Upgrade ratio vs size

It can be seen that for the finest size range, the upgrade ratios are about the same but for the coarser sizes, they show relatively large differences. The data are insufficient to draw any conclusions but it does seem from the results presented above that the conventional cells at Tsikondeni are more effective at recovering the coarser size fractions. One should, however, also keep in mind that the coal at Tsikondeni is very different from the coal at Koornfontein.

4.3 De-sliming tests

The results obtained from the de-sliming tests are shown in Figures 10, 11, 12 and 13.

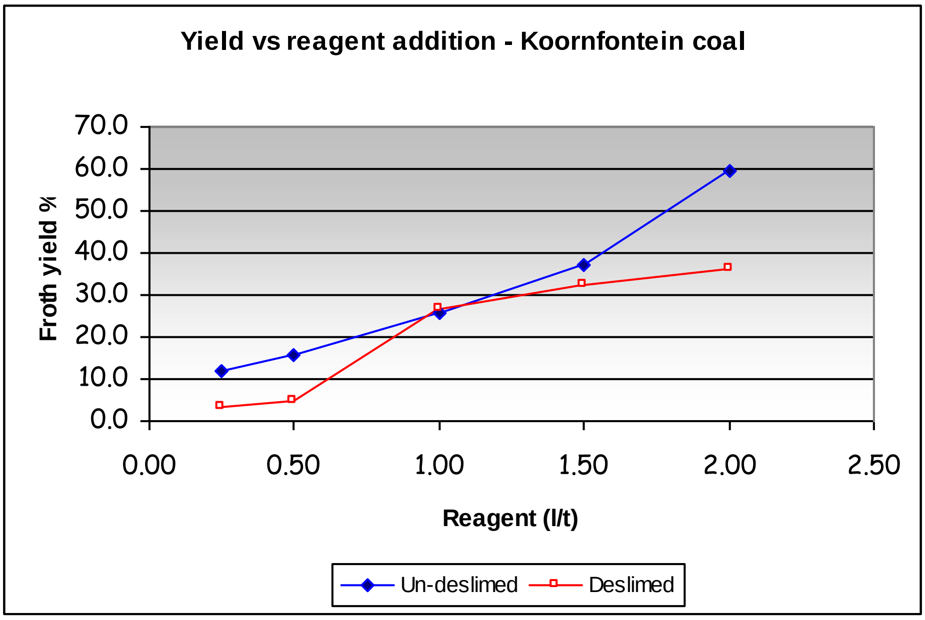


Figure 9: Yield vs reagent addition for Koornfontein coal

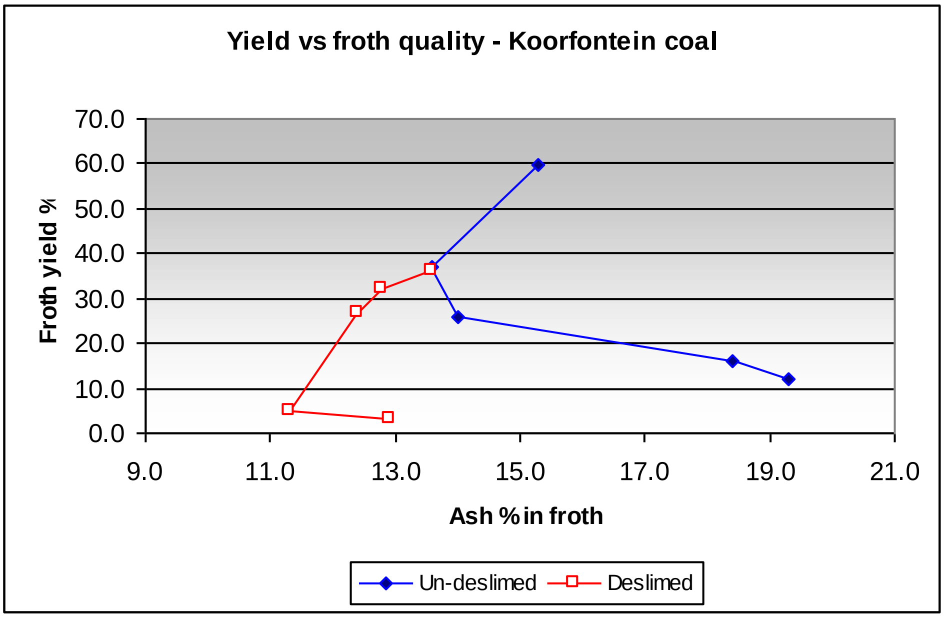


Figure 10: Yield vs ash content for Koornfontein coal

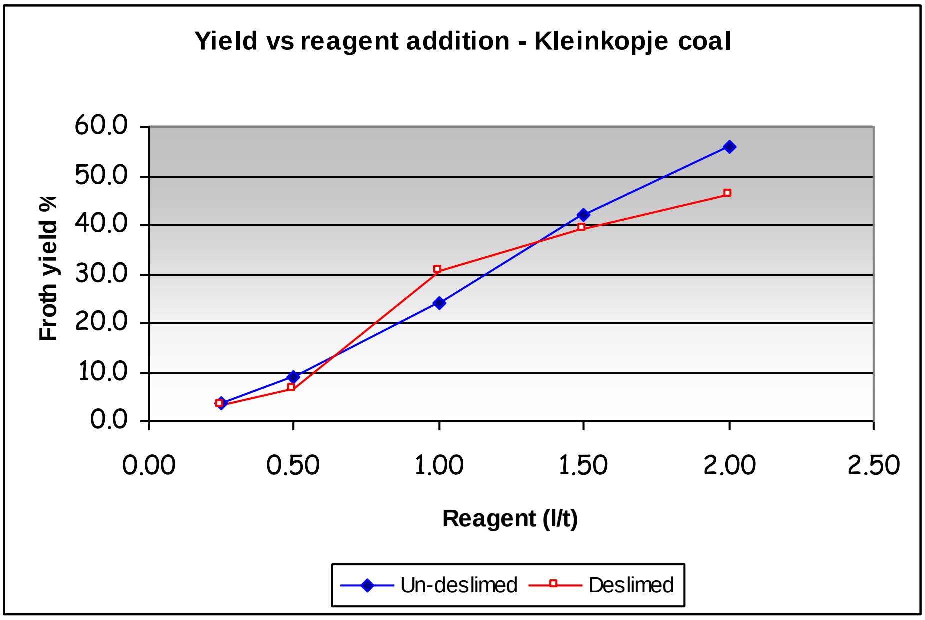


Figure 11: Yield vs reagent addition for Kleinkopje coal

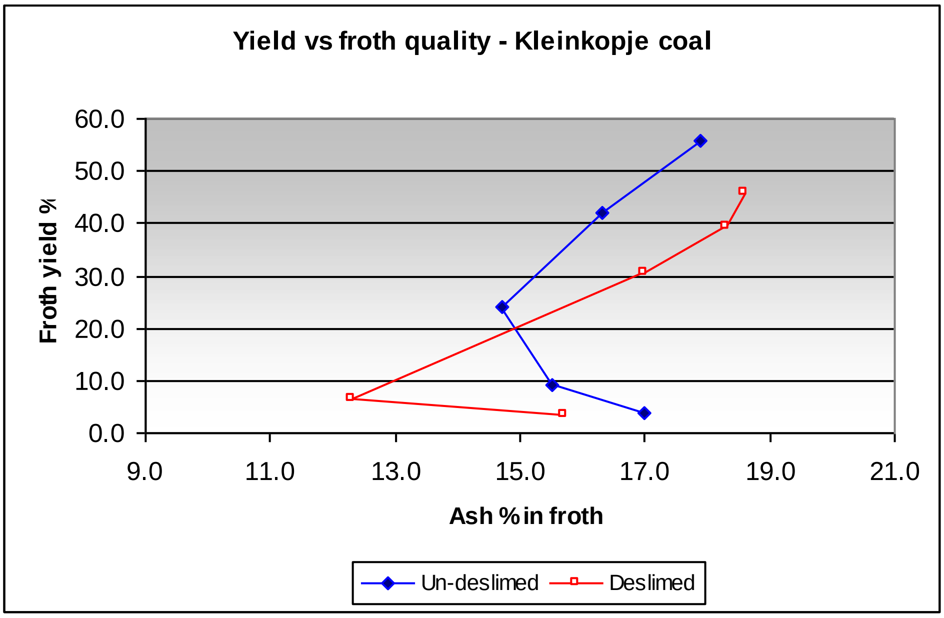


Figure 12: Yield vs ash content for Kleinkopje coal

The amount of minus 25 micron coal removed from the minus 150 micron feed is approximately 40 % in the case of Kleinkopje coal and 60 % in the case of Koornfontein. After de-sliming, the coarser coal yielded higher amounts of product than the un-deslimed coal for the same amount of reagent added. Accounting for the minus 25 micron coal removed during de-sliming results in effective net yields that are lower than the yield achieved on the un-deslimed feed in the case of Koornfontein. For the Kleinkopje coal, the resulting yields are more or less comparable.

In the case of the Koornfontein coal, the product ash values achieved are lower than those achieved on the un-deslimed coal. This is especially true for the low reagent addition rates where the difference in ash content is quite large.

In the case of the Kleinkopje coal, the ash content of the de-slimed coal is higher than that of the un-deslimed coal. It is only at the low reagent addition that the de-slimed product ash exhibits a lower ash value.

It is interesting to note the 'reversal' in ash content obtained at low reagent addition rates. It appears as if at the low reagent addition rates, only higher-ash coal is placed into the product. As the reagent addition increases, the ash content reduces to a certain level before it starts to increase again.

It may be anticipated that the de-slimed froth products would be easier to dewater and this should result in lower product moistures. However, this aspect was not investigated as part of this project. The calculation shown in Figure 13 nevertheless serves to illustrate the effect that de-sliming of the flotation feed may have on the filtration of the resulting froth flotation product.

In the literature[3], the following relationship is indicated between the percentage of minus 75 micron material in the feed to drum filters and disk filters and filter capacity. This relationship has been established empirically.

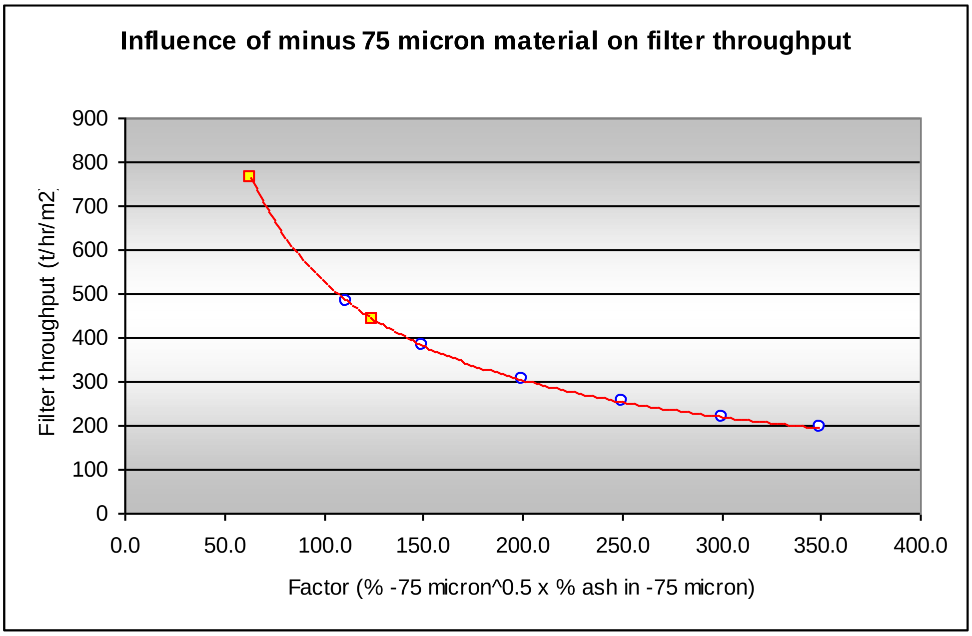


Figure 13: Influence of minus 75 micron material on filter capacity

The Koornfontein froth product contains 82,1 % of minus 75 micron material. If the feed to the cells is de-slimed, this will be reduced to 27,1 %. The filter capacity values corresponding to these percentages of minus 75 micron material are 441 t/h/m2 and 762 t/h/m2 respectively if one uses the relationship as shown in Figure 13 in which these data-points are shown as 'squares'. This represents a 172 % increase in the relative filterability of the froth product.

The percentage of minus 75 micron material in the filter feed also influences the moisture content of the filter cake obtained. The relationship between filter cake moisture and minus 75 micron material in the feed is shown in Figure 14. The data in this figure have, as in the case of Figure 13, been determined empirically.

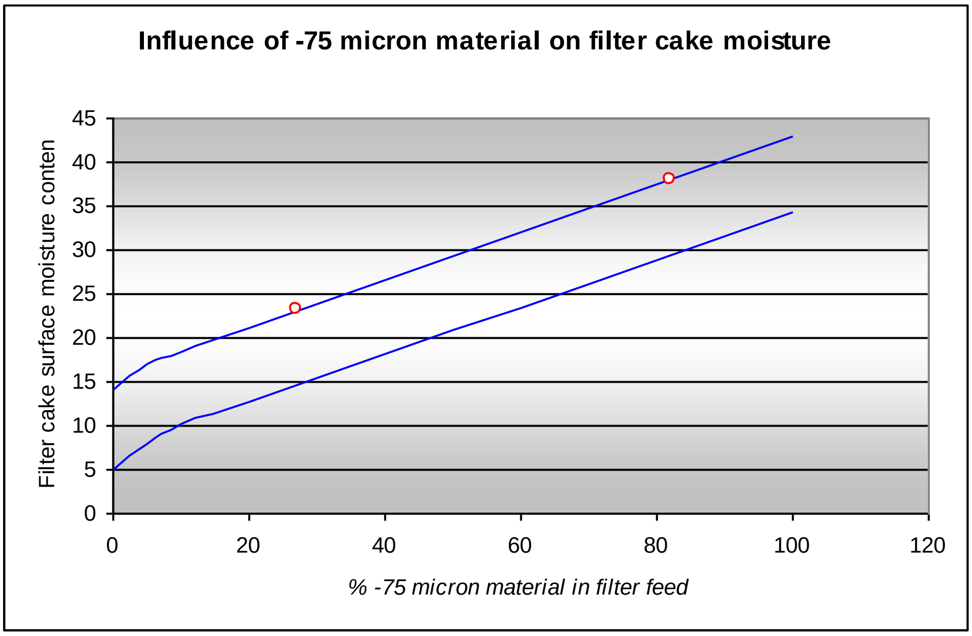


Figure 14: Influence of –75 micron material on moisture content of filter product

In practice, the moisture content of the filter product is normally found to fall between the two lines representing the upper and lower limits.

For the Koornfontein example, the moisture contents of the de-slimed and un-deslimed froth products are indicated in Figure 14 as the points at 23 % and 38 % moisture respectively. If this reduction could be realised in practice, it would be very significant.

An economic simulation was carried out using the results obtained on the Koornfontein coal and assuming that the moisture reduction as indicated above in Figure 14 is achieved. This analysis, attached as Appendix A, indicates that it may be economically viable to de-slime the feed to flotation. Some of the assumptions made will, however, need to be confirmed in practice.

A negative factor that needs to be kept in mind is the fact that if the minus 25 micron material is removed from the flotation feed, this material will need to be disposed of in an environmentally acceptable manner. The cost of this must be weighed against the advantages to be gained from de-sliming.

5. CONCLUSION

Based on the results presented, it cam be concluded that, provided the feed coal is not oxidised and is ‘amenable’ to flotation, froth flotation is a relatively effective process.

It would appear that there may be some truth in the belief that column cells tend to be more effective in beneficiating the ultra-fine size fraction. However, the results presented here cannot be taken as conclusive proof of this and a much more thorough investigation is required. It is hoped that the efforts of Ingwe Coal at Koornfontein will provide the final answers in this regard.

Although only a cursory investigation could be carried out on the potential of de-sliming the feed to flotation, the results indicate that it may be expedient to conduct a more thorough investigation.

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Appendix A

Economics of de-sliming feed to flotation

De-sliming Options - Dolan Colliery	1	2
ROM tons = 2,000,000 per annum **Produce 6 100 kCals/kg NAR product** Basis = 100 tons of plant feed	**Case 1** **No de-sliming**	**Case 2** **De-sliming**
Tons ex Cyclone	58.61	66.07
Tons ex Spirals + Flotation	8.34	7.18
Total	66.95	73.25
CV ex Cyclone	28.64	28.21
CV ex Spirals + Flotation	27.48	27.62
Combined MJ/kg AD	28.50	28.15
Moist ex Cyclone	7.85	7.85
Moist ex Spirals + Flotation	23.65	17.34
Combined	9.82	8.78
Combined - inherent moist	3.00	3.00
CV Kcals GAR	6328	6323
FOB Price (R/t GAR)	R 191.16	R 191.16
Tons railed per annum	1440235	1557831
Railage + Port fees per annum	R 72,011,771	R 77,891,545
Revenue per annum	R 275,315,401	R 297,794,953
Contribution per annum	**R 203,303,631**	**R 219,903,409**
Variance from Base Case	**R 0**	**R 16,599,778**

Case No :	1	2
	Case 1 **No de-sliming**	**Case 2** **De-sliming**
Tons per annum :		
Spiral Product	166,800	143,600
Spiral Feed	160,000	160,000
Flotation feed	100,000	40,000
Flotation Product	59,600	36,300
Discards	661,000	535,000
Operating cost :		
Dewatering screen	R 0	R 0
Centrifuge	R 0	R 0
Flotation	R 1,500,000	R 600,000
De-sliming	R 0	R 100,000
Filtration	R 104,300	R 63,525
Discard Disposal	R1,070,820	R866,700
Total	R2,675,120	R1,630,225
Net Contribution	R 200,628,511	R 218,273,184
Variance from Base Case	**R 0**	**R 17,644,673**

Capital cost :		
Dewatering Screen	R 0	R 0
Screenbowl centrifuge		
Horizontal belt filter		R 0
Hyperbaric filter		
Thermal dryer		
De-sliming plant		1000000
Spiral plant		R 0
Total Capital spent	R 0	R 1,000,000

Net Present Value		
Contribution per annum	**R0**	**R17,644,673**
Capital Cost	**R0**	**R1,000,000**
Net Present Value over 10 yrs	**R0**	**R81,199,538**

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