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Dewatered tailings disposal – a cost effective alternative to wet disposal

M.J. Gowan
Golder Associates Pty Ltd, Brisbane, Australia

ABSTRACT

A coal mine in Mozambique, southern Africa, produces both metallurgical and thermal coal. A relatively high volume of coal washery wastes are produced due to a low average yield. Currently, the tailings are deposited as a slurry in a surface tailings storage facility (TSF1), while the rejects are hauled for disposal in dumps within the mine overburden. Due to the low dry density achieved by the settled tailings and the lack of suitable sites for new TSFs, dry disposal needs serious consideration for future tailings handling.

This paper outlines the current tailings disposal issues and the potential dry disposal solution based around results from a pilot dewatering plant that was established to trial the most effective way of dewatering the tailings. The pilot plant was designed to trial the dewatering effectiveness of a paste thickener, a belt press filter and a centrifuge. The results indicate that the tailings can be effectively dewatered, a dewatered solution would be cost effective, tailings can be transported without issue and mixed with the rejects for co-disposal. Dewatering would eliminate the need to construct any further TSFs, increase the water recovery and reduce tailings disposal costs over the life of the mine.

Key Words: co-disposal, pilot, dewatering, filter, centrifuge, NPV

1 INTRODUCTION

Mozambique has extensive, mainly untapped, coal reserves and this mine is the largest coal mine developed to date. It produces principally metallurgical coal, with a low yield of 35 to 45%, meaning that over the life of the mine until 2047 it will produce an estimated 840 Mt of coarse rejects and 105 Mt of tailings.

The Karoo age sediments at the mine consist of conglomerates, sandstones, shales and coal seams, deposited in a graben-controlled basin. The main coal seam present is called the Chipanga and is approximately 30 m thick. It is divided into three sub-seams and within each of these sub-seams there are further splits. However, for product definition, only four coal seams are currently mined.

Currently, the rejects are hauled to the mine and encapsulated with the mine waste in cells in an out-of-pit dump, while the tailings are deposited into a valley TSF, which is due to be filled in 2018. The mine site has a limited surface area, is relatively flat and has few valleys in which further TSFs can be built. Thus the mine commissioned a study into alternative tailings disposal options, specifically dry disposal.

2 CURRENT TAILINGS DISPOSAL

The tailings are pumped as a slurry, aiming for a solids concentrations in the range from 25 to 35%, through two 355 mm HDPE pipelines to TSF1, over a distance of about 2 km from the coal handling and preparation plant (CHPP).

2.1 Coal seams

Currently the mine processes four coal seams through the CHPP. These seams vary in thickness and occurrence and it is expected that their geotechnical behaviour will differ from each other. For instance, reports from the CHPP record that the one of the seams (UCT) was very difficult to wash.

Early geotechnical test results for three of these coal seams are presented in Table 1. Of note from these results are the following:

- The tailings have a lower specific gravity (SG) than that expected for coal in South Africa and Australia (typically about 1.7)
- The dry density of the deposited tailings is low, from 0.45 to 0.55 t/m³, much lower than the maximum dry density achieved on Standard laboratory compaction (Table 1).

Table 1. Tailings geotechnical test results.

Coal band	SG	Permeability (m/s)	Percentage passing 75 µm (%)	Maximum dry density (kg/m³)	Optimum moisture content (%)	Friction angle (°)	Cohesion (kPa)
LC 45/46	1.453	5.1×10^{-8}	61	1 018	17.4	34.0	0
MLCB	1.529	1.9×10^{-7}	61	1 077	18.0	36.7	0
UCB	1.463	3.3×10^{-8}	42	1 089	16.4	30.8	15.5
Average	1.482	9.1×10^{-8}	55	1 061	17.27	33.8	5.2

Using the data in Table 1, it is estimated that the maximum dry density the tailings could reach on consolidation and desiccation in TSF1 would be about 0.74 t/m³, equivalent to a void ratio of 1.0.

2.2 Tailings Storage Facility 1

TSF1 is a valley containment with a capacity of 23.57 Mm³, a 30 m high main embankment at the northern end of the valley and a 15 m high embankment at the southern end. The tailings are discharged off the main embankment only, through a series of spigots, set at 100 m centre-spacing along the two slurry pipelines.

A tailings dry density of 0.9 t/m³ was assumed during the design phase to determine the filling rate and life of TSF1. Recent field surveys have indicated that TSF1 is only achieving an average dry density of about 0.6 t/m³. This means that TSF1 is filling far more rapidly than was planned and there is an urgent need to provide future tailings storage capacity.

2.3 Tailings Storage Facility 2

In 2006, a tailings disposal feasibility study was carried out and a site to the south of the CHPP was selected as the preferred TSF site. This site had a capacity of just under 80 Mm³ and at the time was expected to provide life-of-mine (LOM) tailings storage capacity. However, instead the TSF1 site was selected for the first TSF.

Since then, the mine has built an ore conveyor across the western edge of this site, now earmarked for TSF2, and they are planning to develop a small pit across its footprint; both of which will reduce its storage capacity to around 53 Mm³. Hence, with both the smaller storage capacity and a planned increased LOM tailings tonnage, TSF2 no longer meets the LOM tailings storage capacity.

2.4 Other TSF options

Upstream raising has been considered for the TSFs, but due mainly to the high rates of rise, in excess of 2 m/year, and the unsuccessful attempts to raise coal tailings TSFs upstream in South Africa, this option was rejected. As the mine is surface area-constrained, and although there may be an opportunity to use a pit sometime in the future, there is currently no free land that could be considered for a third or subsequent TSFs. As a result, the mine has had to consider alternative tailings disposal options, including dewatered (dry) tailings disposal.

2.5 Dry tailings disposal options

A desk-top trade-off study was carried out in 2012 to select the best option to handle the tailings. Alternative tailings disposal options included re-mining and re-processing the tailings, in-line flocculation and a range of dewatering methods.

Capital and operating costs were estimated for these options and, surprisingly, the construction and operation of conventional TSFs did not come out to be the lowest cost option. The lowest LOM cost options were centrifuging and belt press filtration of the tailings and then, after mixing with the rejects, hauling the combined rejects and tailings to the mine for disposal.

The other benefit of installing a dewatering system, other than the apparent benefits of lower costs and meeting the tailings storage requirement, is the increased, and guaranteed, percentage of the process water that can be recovered for reuse, rising from 44 to around 84%.

Further, a selection risk ranking was developed and the combinations of tailings dewatering, transport and disposal location options were compared to obtain an overall priority for each combination and the top eight ranked options are listed in Table 2.

Table 2. Top 8 ranked disposal options.

DEWATERING SYSTEM	TRANSPORT	DISPOSAL LOCATION	RANKING
Belt filter	Belt conveyor	Ex-pit and In-pit co-disposal	1
Belt filter	Belt conveyor	Stand-alone facility	2
Belt filter	Truck	Ex-pit and In-pit co-disposal	3
Belt filter	Truck	Stand-alone facility	4
Centrifuge	Belt conveyor	Ex-pit and In-pit co-disposal	5
Centrifuge	Belt conveyor	Stand-alone facility	7
Centrifuge	Truck	Ex-pit and In-pit co-disposal	6
Centrifuge	Truck	Stand-alone facility	8

2.6 Assessment of dry tailings disposal options

Golder was then commissioned to carry out a scoping level study into the option of moving to dry tailings disposal. Samples of each of the coal seams available at the time were collected and dispatched to tailings dewatering equipment suppliers in South Africa and the USA, namely:

- Belt press filter (BPF) Phoenix
- Centrifuge Alfa Laval

The BPF and centrifuge suppliers delivered positive outcomes from bench-scale testing and confirmed that the tailings should be straightforward to dewater using the supplier’s equipment, producing a low moisture content, handleable cake that could be transported and dumped.

As a result of these tests, the following numbers of units were suggested by each supplier:

- Belt filter press 26 to 36 x 3 m wide units
- Centrifuge, solid bowl up to 5 x 1 m diameter units.

The rejects-to-tailings dry mass ratio over the LOM averages about 8:1. Calculations predicted that all of the tailings could be encapsulated within the void space of the rejects without adding to the volume required to store the rejects alone.

3 PILOT TAILINGS DEWATERING TESTING

In view of the favourable results for the mechanical dewatering options and considering that this would be a radical tailings disposal departure for the mine, it was agreed that there would be benefit in running and demonstrating the dewatering equipment at pilot-scale in real-time before making a final decision. The pilot plant study was commissioned in the third quarter of 2013, with the Golder scope to design and manage an on-line pilot testing study of a paste thickener, belt press filter and centrifuge.

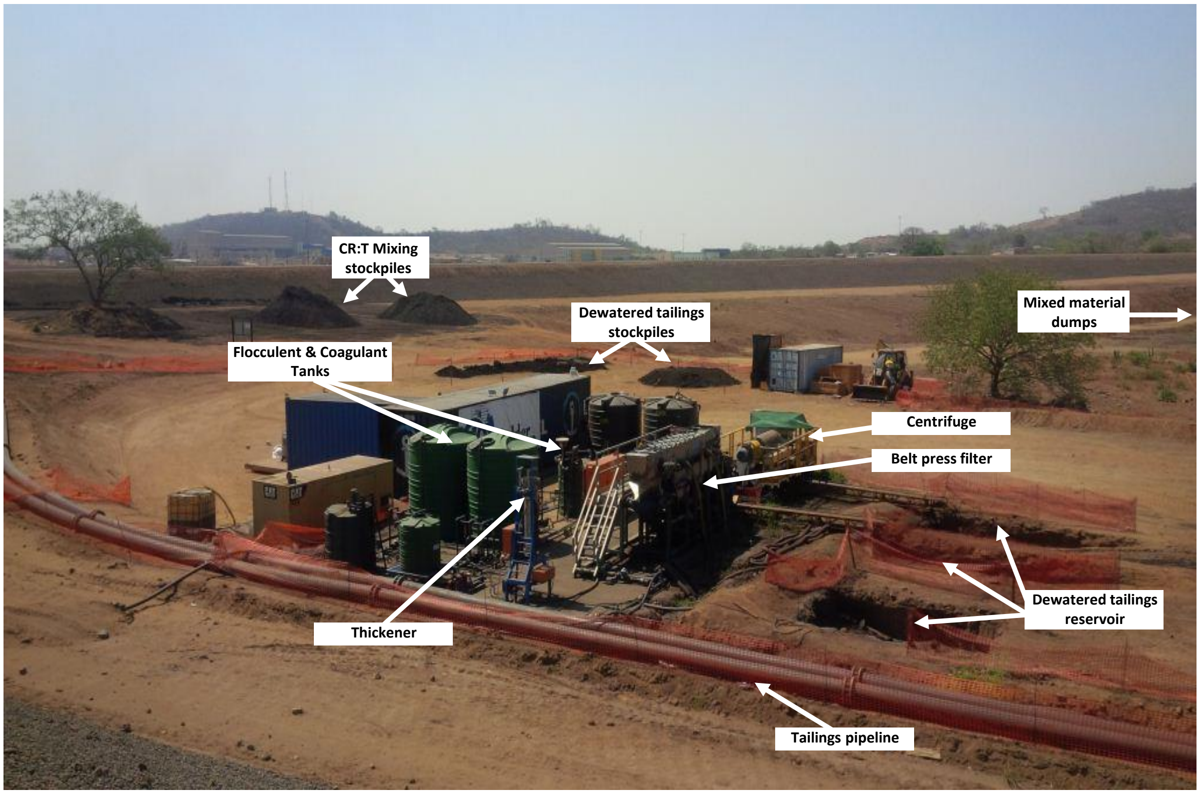

Figure 1. Pilot plant arrangement.

3.1 Pilot equipment

A site for the pilot testing was selected within the footprint of TSF1, on high ground in the north east corner (Figure 1). This site was adjacent to the slurry pipelines, close to the water supply line and was unaffected by daily CHPP operations.

The infrastructure to support the pilot equipment was designed, procured and fabricated by the Golder engineering team in its Centurion (South Africa) workshop. The equipment consisted of:

- Flocculent mixing tanks, dosing pumps, piping and electrical controls
- A water supply tank and pumping system to supply washing water to the belt filter press
- Electrical reticulation for the dewatering units and pumps.

This infrastructure was erected on a prepared concrete slab. Shipping and importing this equipment into Mozambique proved challenging, but eventually a reliable transporter was identified and used.

3.2 Paste thickener

The 300 mm diameter pilot paste thickener was fed with a dedicated slurry feed system. Flocculent and coagulant were added at a rate of 100 g/t each and the resulting underflow solids content varied between 48.2% and 51.1%, occasionally reaching 56%. This compares very favourably with the underflow solids content of between 27% and 31% achieved in laboratory testing at a flocculent dosage rate of 100 g/t.

The thickener underflow was pumped into a receiving cell so that field testing could be carried out. The tailings beach measured around 3%. The dry density of the settled paste tailings was measured at about 0.82 t/m³.

3.3 Belt filter press

Andritz supplied and operated a 1 m pilot belt press filter (BPF). A summary of the filter cake moisture contents results obtained is given in Table 3.

Table 3. Moisture content in cake produced by the BPF.

PARAMETER	UNIT	SLURRY DENSITY (T/M^3)				
		1.1000	1.1000	1.1036	1.1013	1.1036
Solids concentration	%	28.4	28.4	29.4	28.8	29.4
Belt speed	m/min	7.3	9.7	7.7	8.6	7.7
Cake thickness	mm	11	12	12	12	12
Slurry throughput	t/hr	0.6	0.8	0.6	0.8	0.6
Flocculent usage	g/t	888	767	514	480	900
Coagulant	g/t	0	0	0	0	0
Filter cake water content	%	17.5	16.5	15.8	16.2	18.3

The results of the belt press filter field trials are shown in Table 4, and are compared with the results of the laboratory testing carried out by Phoenix on three coal seams. The field and laboratory BPF dewatering rates are very similar, with the major difference being the flocculent dosage rates.

Table 4. Belt press filter outcomes.

PARAMETER	UNIT	FIELD	LABORATORY
Feed solids concentration	%	28 - 30	35
Expected operational belt speed	m/min	5 - 10	
Expected flocculent dosage	g/t	500 - 600	100
Expected cake water content	%	18 - 25	30
Expected cake thickness	mm	9 - 11	
Tailings dewatering rate	t/m/hr	11	6.2 to 8.4

Of note were:

- The flocculent dosage rate had to be increased, from the 100 g/t estimated from the original bench-scale tests, to between 500 and 600 g/t to achieve a filter cake with 18-25 % by mass water content
- Coagulant was not needed, as its addition did not contributing for the final moisture content
- The filter cake produced by the BPF broke off in slabs, which then broke down into smaller, but still quite large and stiff platelets when discharged from the conveyor
- When the BPF was loaded and working efficiently the filtrate was reasonably clean.

The conclusions that can be drawn from this testing are that:

- The belt production rates measured in the field tally closely with those predicted from laboratory testing, so the number of belt filter presses required did not change significantly from the number predicted
- The flocculent dosage rates in the field trials are significantly higher than predicted in the laboratory, which increases the flocculent operating costs significantly
- A more efficient flocculent may be found through a flocculent screening study, with the aim of reducing the demand.

Andritz have recommended that 19 operating belt press filters will be required to meet the planned slurry solids concentrations range and the tailings output of 570 tph.

3.4 Centrifuge

The results of the centrifuge testing were very encouraging and test results are shown in Table 5.

Table 5. Range of centrifuge cake moisture contents.

Slurry solids range (%)	Slurry feed RD	% Solids	Bowl speed (rpm)	Scroll speed (rpm)	Slurry (m³/hr)	Solids (t/hr)	Flocculent usage (g/t)	Water content (%)
20 to 25	1.082	23.8	1 200	20.0	15.0	3.9	583	29.0
20 to 25	1.080	23.2	1 700	8.0	21.3	5.3	150	24.7
20 to 25	1.080	23.3	1 900	5.0	21.5	5.4	0	21.4
25 to 30	1.100	28.4	1 700	8.0	21.5	6.7	186	24.4
25 to 30	1.105	29.7	1 800	5.0	20.0	6.6	0	22.4
30 to 35	1.099	28.2	1 900	9.3	19.9	6.2	0	23.6
35 to 40	1.116	32.6	1 900	5.0	20.5	7.4	0	31.4
35 to 40	1.160	43.1	1 800	9.0	19.8	9.9	0	23.6
35 to 40	1.139	38.2	1 900	6.5	20.0	8.7	0	23.3

The following points are of note:

- A handleable cake could be achieved using no flocculent
- The cake dry density results using no flocculent were often better than those using flocculent
- A cake moisture content of around 22% by mass could be achieved
- The cake water contents are slightly lower than achieved by the BPF
- The cake water content increases with slurry feed solids concentration
- The centrate looks much cleaner (lower solids concentration) than that from the BPF.

The pieces of cake produced by the centrifuge were smaller and slightly softer than produced by the BPF.

3.5 Recommended equipment numbers

The results of the pilot testing indicated the following design numbers for the dewatering equipment (Table 7):

Table 7. Design numbers for dewatering equipment

EQUIPMENT	THROUGHPUT	NUMBER	FLOCCULENT DOSAGE RATE (g/t)
Belt press filter	10 t/hr/m	19	500 - 550
Centrifuge	55 tph/machine	13	350

4 TRANSPORT AND DISPOSAL PROCESS

4.1 Field and laboratory testing at Moatize

The intention is for the dewatered cake to be dropped on to the rejects belts and discharged into the rejects bin, allowing time for mixing with the rejects prior to being hauled to the rejects dump for disposal. There will be no increased haulage cost or increase in the rejects dump size if the rejects and tailings are mixed at the expected 8:1 ratio.

Field testing of the dewatered tailings cakes produced by both the BPF and the centrifuge were performed to understand their geotechnical parameters and to demonstrate that the addition of tailings to the rejects would not change their handling or placement characteristics. The field and laboratory testing program was developed to test the following:

- Loose and compacted dry density of the two cake products
- Handling characteristics of the cakes
- Mixing characteristics of the cakes with rejects
- Loading characteristics of the mixed products
- Loose and compacted dry densities of the mixed products
- Trafficability of the mixed products when dumped and placed.

4.2 Cake handling

A backhoe was used to recover the cake from the dump at the end of the product conveyors and to transport it to temporary stockpiles. The cakes loaded easily, did not stick to the bucket and formed stable stockpiles. A difference was noted between the stockpiles of dewatered tailings cake from the BPF and the centrifuge:

- The dewatered tailings stockpile produced by the centrifuge formed large balls (about 150 mm in size) that rolled to the base of the stockpile and did not break easily
- No such balls were evident on the dewatered tailings stockpile produced by the BPF, where the dewatered tailings remained as wedges that were easily crushed underfoot.

4.3 Mixing coarse rejects and tailings

The backhoe was used to mix the coarse rejects with dewatered tailings in the ratio 8:1. The mixtures were then loaded into a dump truck and hauled about 500 m to separate test dumps, where the rejects-tailings mixture was spread and track-rolled. It was noted that the freshly dewatered tailings from both the BPF and the centrifuge mixed easily with the coarse rejects, did not stick to the TLB bucket or cause any sticking during mixing and offloading from the dump truck.

Mixing was achieved easily and to the naked eye there was no difference in the texture of the two dumps. Samples taken from the mixed dumps were tested in the site laboratory and gave the following dry density results (for the BPF and centrifuge processes):

- Loose without compaction 1.38 to 1.14 t/m³ respectively
- Compacted 1.44 to 1.40 t/m³ respectively.

The difference in the two cakes discussed above may be the reason there is such a significant difference between the loose dry density of the BPF and centrifuge mixed products.

A field density test was carried out on an 8:1 coarse rejects-to-tailings mixture after being dumped, spread and rolled. The result was a dry density of 1.76 t/m³, a 22.5% increase over the laboratory testing, showing the benefit of controlled compaction.

4.4 Dynamic cone penetration testing

DCP testing was carried out on test dumps of the 8:1 rejects-to-tailings mixtures prepared with both the BPF and the centrifuge cakes. The results suggest that:

- There is little difference in the bearing strength of the BPF (CBR 14 to 28) and centrifuge (CBR 22 to 30) rejects-to-tailings mixtures
- The rejects-to-tailings mixtures will "go down" easily and with minimal compaction will be able to support the mine's haul fleet.

Experience at the mine has shown that the haul trucks are able to traverse the rejects when they are dumped without tailings. The DCP results suggest that the addition of tailings will not detract from this and that the mixtures achieve a CBR of 10 or greater with minimum effort, which means that it will support the mine haul traffic.

4.5 Field density testing

Due to the large particle size of the coarse rejects, of up to 75 mm, a conventional sand replacement test could not be used, so instead a large water replacement test was used. The results obtained for 8:1 coarse rejects-to-tailings mixtures are shown in Table 6.

Table 6. Field bulk densities of dumped mixed rejects: tailings.

TAILINGS CAKE ORIGIN	FIELD BULK DENSITY (t/m³)
BPF	1.764
Centrifuge	1.799
TSF1	1.019

5 CLASSIFICATION TESTS

The tailings proved to be non-plastic. They have a very low clay mineral content or clay-size, and are classified as a silty sand, as shown in Table 7.

Table 7. Tailings indicator and particle size distribution test results.

Seam	Source	Plasticity Index (%)	Liner Shrinkage (%)	Sand-size (%)	Silt-size (%)	Clay-size (%)	Unified Class
LC45/46	Centrifuge	0	0	52	30	18	ML
LC45/46	BPF	0	0	63	31	6	ML
LC45/46	Slurry	0	0	50	40	10	SM
LC45/46	Centrifuge	0	0	64	30	6	SM
MLCU	Centrifuge	0	0	50	40	10	ML
MLCU	BPF	0	0	66	28	6	ML
MLCU	Centrifuge	0	0	65	29	6	ML
MLCU	Centrifuge	0	0	68	29	3	SM
UCB	BPF	0	0	66	32	2	ML
UCB	Centrifuge	0	0	58	37	5	ML

5.1 Moisture content

The moisture and water content of the as-received dewatered tailings samples are shown in Table 8.

Table 8. Tailings moisture contents.

Seam	Source	Moisture Content (%)	Water Content (%)
LC45/46	Centrifuge	24.6	19.7
LC45/46	BPF	30.7	23.5
LC45/46	Slurry	10.1	9.2
LC45/46	Centrifuge	0.0	0.0
MLCU	Centrifuge	15.6	13.5
MLCU	BPF	23.3	18.9
MLCU	Centrifuge	21.2	17.5
MLCU	Centrifuge	20.5	17.0
UCB	BPF	28.2	22.0
UCB	Centrifuge	27.2	21.4

The results given in Table 8 agree with the total moisture contents determined by Andritz for dewatered tailings collected from the BPF and centrifuge:

- BPF 18 to 21%
- Centrifuge 22% average.

5.2 Test results for mixed samples

The particle size data for the mixed rejects and dewatered tailings, in the ratio of 8:1, show the mixtures to be predominantly gravel and non-plastic, as expected (Table 9).

Table 9. Indicator and particle sizing of mixed materials.

Seam	Source	PI (%)	LS (%)	Gravel-size (%)	Sand-size (%)	Silt-size (%)	Clay-size (%)	Unified Class
LC45/46	Centrifuge	0	0	77	18	4	1	GP-GC
MLCU	BPF	0	0	77	18	4	1	GP-GC
LC45/46	Centrifuge	0	0	35	33	32	0	GP-GC

A standard compaction test and CBR strength test was carried out on the rejects-to-tailings mixtures and on the rejects alone (Table 11).

Table 10. Compaction and CBR results.

Sample	Source	Maximum Dry Density (t/m^3)	Optimum Moisture Content (%)	CBR @ 93% MDD
LC45/46	Centrifuge	1.672	6.6	48.2
UCB	Centrifuge	1.718	6.1	30.4
MLCU	BPF	1.685	6.1	43.8
Rejects	-	1.746	6.5	30.5

Observations:

- The maximum dry density of the mixed materials was slightly lower, on average by 3%, than the maximum dry density of rejects alone
- The optimum moisture contents were about the same
- The CBR of the mixed materials was up to 58% higher than that of rejects alone, indicating that adding the tailings improves the load bearing capacity of the coarse rejects.

6 CONFIRMATORY LABORATORY DEWATERING TESTING

Samples of the coal tailings were sent to the laboratory Andritz in Europe for confirmatory dewatering testing. The results of this testing, shown in Table 12, include suggestions for hyperbaric and Plate and Frame filters for completeness.

Table 12. Equipment recommendations following confirmatory laboratory testing

EQUIPMENT	NO OPERATING	FLOCCULENT (g/t)
Belt press filter	19	350
Centrifuge	11	250
Hyperbaric filter	6	0
Plate & Frame`	44	0

7 LOM TAILINGS DISPOSAL COSTING

The LOM tailings disposal costing has been developed using the results of the pilot testing, the costing basis established by Golder and dewatering machinery costs from Andritz.

7.1 Infrastructure multiplier update

A construction multiplier was used to factor up the infrastructure costs associated with dewatering equipment, based on discussions with an EPCM contractor with local experience:

- Belt press filter 6.0
- Centrifuges 4.5.

7.2 LOM costs and NPVs for the various dewatering options

The NPV for the various dewatering options and TSFs, have produced the following results (Table 13).

Table 13. Costs for the various dewatering systems

SYSTEM	LIFE (yrs)	CAPITAL COSTS (USD M)	OPERATING COSTS (USD M)	LOM COSTS (USD M)	NPV (USD M)
Hyperbaric	28	97.18	91.01	188.19	-125.80
Centrifuge	28	58.38	278.59	336.97	-148.83
Plate/Frame	28	102.74	169.39	272.13	-156.47
3 m Belt Press	28	97.18	273.49	370.67	-159.19
Single large TSF	28	122.17	88.69	210.86	-173.44
TSF2	9	177.82	23.48	201.30	-185.80
Multiple TSF2's	28	782.21	88.69	870.91	-305.88

While the hyperbaric and Plate/Frame filters produced the most attractive NPVs, they will not be considered further due to:

- Hyperbaric filter - The risks of operating high pressure equipment on a remote site in Africa are considered high
- Plate and frame – high capital costs given that there is no need for a very dry cake.

8 DISCUSSION

The following conclusions are drawn from the dewatering tests:

- For the BPF
  - Production rates measured in the field tally closely with those predicted from laboratory testing
  - The flocculent dosage rate in the field had to be increased, from the 100 g/t estimated from the original bench-scale tests, to up to 550 g/t to achieve an acceptable filter cake water content
  - Subsequent flocculent screening has reduced the flocculent rate to 300 to 350 g/t
- The centrifuge proved to be the most suitable option for dewatering this tailings, indicating:
  - A cake moisture content of around 22%
  - A flocculent dosage rate of around 250 g/t
  - A much cleaner centrate than that from the BPF.
- The dewatered tailings
  - Did not stick to the bucket when loaded, so should not stick to conveyor belts
  - Can be mixed easily with the rejects and produces a dump with enhanced geotechnical parameters.

9 CONCLUSIONS

Dewatering the tailings and mixing it with the rejects for co-disposal has been shown to be the most cost effective disposal method for this mine in the future, using the existing rejects trucking and disposal system, and centrifuges have been recommended as the preferred dewatering equipment.