SECTION 11

THE DESIGN OF A CO-THICKENED SLIMES DISPOSAL SYSTEM FOR THE KIMBERLEY COMBINED TREATMENT PLANT

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ABSTRACT: De Beers Kimberley Mine has recently commissioned a new treatment plant to re-treat old diamond bearing kimberlite waste dumps. A high density slimes disposal system incorporating deep cone raked paste thickeners and high pressure positive displacement pumps was installed.

Thickening of kimberlite slimes to high underflow densities is often difficult and careful selection of thickening equipment was necessary in order to ensure that the design densities could be achieved. Thickened kimberlite slurries also exhibit non-Newtonian flow behavior with rheology that can vary dramatically at constant slurry density. It was necessary to employ innovative control strategies in order to maximise thickened slurry placement densities without exceeding the pressure capability of the pumps and pipeline.

This paper describes the thickening circuit selection and the hydraulic design of the high pressure pumping system.

11.1 INTRODUCTION

Five major kimberlite pipes in the Kimberley area (South Africa) have been mined on a large scale since the discovery of diamonds in 1872.

At the time a technique known as “flooring” was a commonly practiced comminution process for liberating diamonds from the hard “blue ground” ore. The technique involved laying the ore out over a large area and allowing the material to weather naturally. The softer weathered ore would then be amenable for diamond recovery using pans. Discards from the flooring and pan processes produced the various dumps surrounding Kimberley today. Due to the crude recovery technologies employed, almost all of these dumps contain diamonds and therefore represent a significant mineral resource (Table 11.1).

The current treatment plant which was established in 1957 and makes use of outdated pan recovery technology should have come to the end of its metallurgical life in the late 1980’s. Arising from a feasibility study conducted in 1998/1999, it was found to be economically viable to construct a new Combined Treatment Plant (CTP) to continue to treat the fresh ore from several operating underground mines and to re-treat material from the old surface dumps. The plant would have a design head feed capacity of 1000 t/h.

An ore dressing study to determine dump ore and diamond characteristics was subsequently conducted by De Beers in order to provide input to the CTP metallurgical flow sheet design. The study indicated a high variability in ore characteristics between the various resource reserves which would impose significant process challenges to the plant. To reduce variability, a feed stock comprised of a "mixed-dump" blend of the ores would be delivered to the CTP (Table 11.1).

An engineering, procurement and construction management contract for the major portion of the CTP project was awarded to Fluor Daniel SA (Pty) Ltd in April 2000 and site construction commenced in August 2000. De Beers provided the specialist input towards the design of the water recovery and thickening circuit, while Paterson & Cooke Consulting Engineers (Pty) Ltd (PCCE) provided specialist testing and design services relating to the slurry pumping system. Commissioning of the system has been completed and full production should be achieved during 2003.

Table 11.1 The CTP resource reserve

Resource Name	**Resource Reserve (million tonnes)**	**Mixed-Dump Blend (%)**
ODTP	45.3	25
Kenilworth	12.4	25
Boshof	19.5	23
Collville	4.2	4
Reservoir	8.5	13
Pulsator	1.6	2
Underground	4.1	8
Total	95.7	100

11.2 CO-THICKENING SYSTEM OVERVIEW

Feed to the CTP consists of trucked dump material and ore from the underground operations which is transported by conveyor. The ore is blended and treated by conventional scrubbing, screening and dense media separation (DMS) processes followed by a state of the art dry recovery process.

Typically diamond tailings products cover a wide particle size distribution and are grouped into three distinct size classes; a barren coarse gravel stream (-8 mm +1.5 mm); an intermediate "grits" stream (-1.5 mm +0.3 mm) and a fine "slimes" slurry (-0.3 mm).

Traditionally, both the coarse gravel and grits streams are conveyed to a dump, while the slimes are thickened in conventional thickeners and relatively low density underflows are pumped centrifugally to paddock-type disposal dams. In line with a long-term waste management and water conservation strategy, De Beers have in recent years tended to cothicken the grits and slimes streams to achieve a high density product for disposal. Co-thickening results in significant capital and operating cost savings by eliminating the de-gritting section of the plant, reducing the number of conveyors, saving water and reducing the costs of building disposal facilities.

After a further cost/benefit analysis during which the disposal of either low density tailings using centrifugal pumps versus high density tailings using positive displacement pumps was compared, a decision was taken to implement a water recovery and tailings disposal circuit for the CTP based on the paste and thickened tailings principle. As such, the grits and fines tailings streams are co-thickened to generate a high density paste which is pumped to a surface disposal facility by piston diaphragm pumps. In the future several disused open pit mines in the vicinity will be used for disposal of the entire tailings (i.e. including of the coarse gravel which will be transported by conveyor belts).

The following fundamental design parameters were applied to the water recovery and tailings disposal system design:

- Tonnage to be treated: 505 to 610 dry tonnes per hour
- Thickener feed volume range: 5000 to 7240 m^3/h
- Underflow slurry density range: 1.5 to 1.65 tonnes/m^3
- Volumetric flow rate range: 463 to 758 m^3/h
- Initial pipeline length: 5 500 m to surface disposal facility
- Ultimate pipeline length: 3 100 m to disused mining pit

11.3 THICKENING CIRCUIT DESIGN

The design of the thickening circuit was conducted in stages, beginning with the characterization of the ore and raw water sources in order to identify possible problematic combinations. Once the basic characteristics of the components were understood, a process of selecting appropriate flocculants and coagulants for the ore/water combinations was undertaken. In the subsequent stages, the free settling rates of the ore/water and selected flocculant combinations were determined through standard laboratory jar settling tests.

These settling rates were used as the basic design criteria for determining the surface area required for the CTP thickening circuit. Finally, once the surface area requirement had been determined, an adjudication process was undertaken in order to select an appropriate thickening unit for the circuit.

11.3.1 Ore Mineralogy Analysis

Processed kimberlitic tailings, in general, bear a striking similarity to the behavioral characteristics of a class of agriculturally problematic soils known as the “saline and alkali soils”. Three criteria are used to classify the soils (Richards 1969, Vietti 2003).

- The conductivity of an extract taken from a saturated soil provides a measure of the water-soluble cations within the soil (i.e. not bound to the clay fraction).
- The Exchangeable Sodium Percentage (ESP) provides a measure of the amount of sodium ions bound to the clay fraction in the soil (i.e. how sodium ion exchanged the clays in the soils are).
- The pH of the saturated soil.

Using these criteria, soils can be classified into the following groupings:

- *Saline Soils*
  High extract conductivity (i.e. high concentrations of soluble salts present); the ESP is lower than the critical level of 15% and extract pH values are lower than 8.5. Because of the high soluble salt content, the soils are in a "flocculated" state and will form settling slurries if suspended in water.

- *Saline-Alkali Soils*
  The ESP of these soils is higher than the critical level of 15%, however, these soils behave either as saline soils or non-saline-alkali soils depending on the amount of soluble salts present (i.e. their conductivity). If the conductivity of the soils is high, the pH of the soil is lower than 8.5 and the soils remains in a "flocculated' state. If however, the soluble salts are leached out of the soil, the properties of the soil change and they begin to behave as non-saline-alkali soils.

- *Non-saline-Alkali Soils*
  Low extract conductivity, the ESP is greater than 15% and the pH usually ranges between 8.5 and 10. The ESP has a profound effect on the chemical characteristics of the soil. The higher the ESP, the higher the pH and the more the soils tend to disperse. Typically, problematic processed kimberlite ores show behavioral characteristics similar to this category of soil.

Clay mineral analysis of dump auger samples indicated that the dominant clay mineral within the samples across the range of dumps belonged to the smectite group of clays (Figure 11.1). In addition, the clays appeared to be highly sodium ion exchanged and were classified as saline-alkali soils according to the criteria above (Table 11.2)

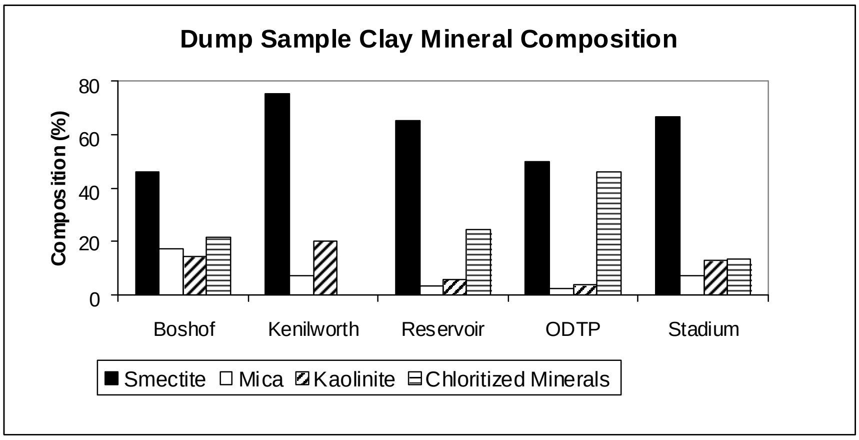

Figure 11.1 Clay mineral compositions of the CTP dump resources.

Table 11.2 Saline-alkali characteristics of the CTP dump resources.

	Boshof	**Kenil-worth**	**Reservoir**	**ODTP**	**Stadium**
Exchangeable Sodium Percentage (%)	80	58	79	70	57
Saturation Conductivity (mS/m)	450	1900	732	620	551
Saturation pH	10.1	9.2	9.9	9.6	9.7

Further, the results indicated that both Boshof and Reservoir dumps were highly alkalized (and potentially most problematic) while the ore from the Kenilworth dump was the least alkalized (and potentially least problematic).

11.3.2 Water Quality Analysis

Another factor, which is vital in determining the ion exchanged nature (ESP value) of the clays, is the chemical quality of the water which contacts the soil.

The alkali hazard potential of water used for irrigation is determined by the absolute and relative concentrations of the cations in the water. If the proportion of sodium in the water is high, the alkali hazard is high and conversely if calcium and magnesium predominate, the hazard is low.

A unit which is used to determine whether a water quality is likely to create clays which are highly sodium ion exchanged (high ESP value) is known as the Sodium Adsorption Ratio (SAR) value of the water. The SAR is the ratio of sodium ions to calcium and magnesium ions in solution and the figures are derived from a normal chemical analysis of the water (in meq/l):

$$\text{SAR} = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$$

Since there is a fairly good correlation between the SAR value for a water and the ESP value of a clay suspended in such a water, the ESP value of the clays in the irrigated soil can be estimated if the SAR of the irrigating water is known (Richards 1969).

The alkali hazard potential of several raw water sources to the CTP were evaluated and described in Figure 11.2.

The results indicated that most of the raw water sources available contained waters which were relatively hard (i.e. low SAR values) ranging from low through to relatively high total cation content, with the exception of one particularly saline water. However, any process waters generated from these waters are likely to become more saline as a result of salts leaching from the ores and as such may present slurry settling problems (Table 11.3).

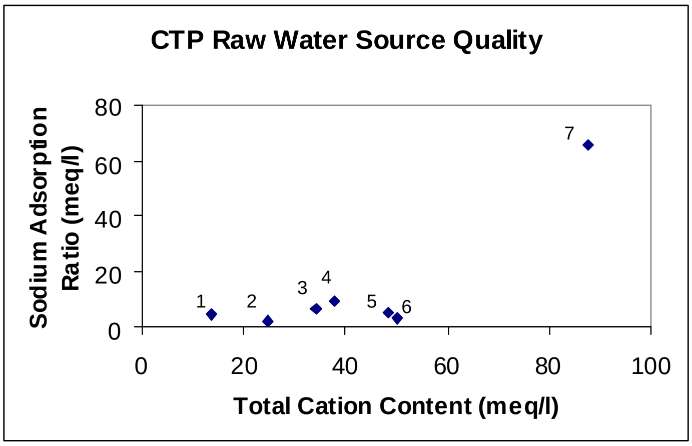

Figure 11.2 Alkali hazard potential of the CTP raw water sources

Table 11.3 Sodium adsorption ratio of the Kimberley dump soluble cation extracts.

	Boshof	Kenilworth	Reservoir	ODTP	Stadium
SAR (meq/l)	2.9	12.4	7.0	9.4	7.5

11.3.3 Slurry Settling Characteristics

A visual settling test was conducted in which slurries from a matrix of raw water and dump ore combinations were generated and was used to confirm the ore and water characteristics information already gathered (Table 11.4).

Table 11.4 Colloidal stability characteristics of the CTP dump and water combinations after 10 minutes settling time.

Resource Name	Raw Water Source						
	1	2	3	4	5	6	7
Boshof							
Kenilworth							
Reservoir							
ODTP							
Stadium							

Settling	Partial Setting	Non Settling

The analysis indicated that colloidally stable slimes were likely to be generated in water derived from raw water source 1, and partially settling slimes in water source 7. The reasons are primarily due to the low cation content in the former water and the highly saline condition of the latter. In addition, Kenilworth dump appeared to be the least problematic ore, while Reservoir dump appeared to be the most difficult to settle.

Ultimately, water source 5 was selected as the most suitable source for supplying raw water to the CTP and on which a flocculant and coagulant selection trial was conducted in order to select an appropriate flocculant/coagulant combination on which the subsequent jar settling tests could be conducted.

A wide envelope of free settling rate velocities for the various flocculated dump slurries was encountered in which certain slurries required coagulant addition, while others did not (Table 11.5). In general slurries with the lowest settling rates were generated from the Boshof dump ores.

Table 11.5 Average free settling rate for the CTP dump slurries.

Resource Name	**Average Free Settling Rate (m/h)**
Boshof	8.6
Kenilworth*	9.7
Reservoir*	9.9
ODTP	19.7

* No coagulant needed

11.3.4 Thickener Area Sizing and Unit Selection

A mass balance exercise based on the CTP design parameters described earlier and on the data provided in Table 11.5 suggested that the total settling area required by the CTP thickening circuit would be in the order of 834 m^2.

Selection of a suitable thickening unit was conducted through an adjudication process in which a range of commercially available high rate/high compression/deep cone thickeners and their critical components were compared.

The components which were considered to be critical to a thickening unit capable of generating and delivering a consistent paste-like underflow were:

- The feed well design – in particular the method in which incoming feed was distributed; any de-aeration devices and any feed solids dilution features.
- Secondary dewatering devices – i.e. the presence or absence of a rake mechanism and specifically the configuration of any attachments associated with the rake.
- The presence or absence of any underflow rheology modification device.
- The presence or absence of any overflow clarification device.

The outcome of the process indicated that in order to satisfy the CTP process requirements, five 15 m diameter Eimco deep cone raked paste thickeners along with the associated flocculant and coagulant dosing plants would be required in the thickening circuit. These thickeners incorporate a pumped recirculation loop to provide shear thinning of the underflow in the thickener compaction zone.

The components of this circuit were expected to deliver a high density paste-like underflow to the subsequent tailings pump and pipeline system.

11.4 PUMPING SYSTEM DESIGN

11.4.1 Slurry Test Work

Co-thickened slimes and grits with a high percentage of –75 μm particles exhibit marked non-Newtonian flow behaviour at high solids concentrations. A series of pipe loop tests conducted by PCCE in 1998 indicated that the slurry can be classified as a Bingham plastic and that yield stress and plastic viscosity increase steeply for slurry densities above 1.50 t/m^3.

After a decision had been made by De Beers to adopt the paste and thickened tailings slimes disposal method for CTP, a further series of pipe loop tests were conducted by PCCE in 2000 using Mixed Dump and Boshof materials. The purpose of these tests was to compare the previous data with freshly prepared and flocculated material and to gather data at the higher slurry densities required for a paste disposal system. De Beers Debtech personnel prepared underflow slurry samples in a pilot scale thickener assembled in the PCCE's Cape Town pipe loop test facility. Samples were thickened up to densities of up 1.59 t/m^3 and tube viscometer tests were performed to determine the slurry flow behaviour.

Both dump materials exhibited time dependent behaviour not recorded during the 1998 test programme. Shear stress increased at a constant shear rate with time and eventually stabilized at a fully sheared value. The rheology of the freshly prepared and flocculated material was generally slightly lower than that measured during the 1998 tests and these differences can be ascribed to different sampling techniques, slurry preparation methods and differences in the degree of particle and flocculant degradation.

11.4.2 Slurry Flow Behaviour

There was considerable variation in the slurry flow behaviour of the two dump materials and this can be attributed mainly to the difference in the -75μm fraction.

Figure 11.3 illustrates the variation in particle size distribution for two samples from distinct dump areas. Table 11.7 indicates a summary of the slurry rheology properties obtained from the test programme. The variation in rheological properties between the two dump materials is apparent.

Table 11.7 Slurry rheology test results

	Boshof Material					
Percentage - 75 μm	43%					
Slurry density (t/m^3)	1.40	1.50	1.60	1.62	1.70	1.75
Bingham yield stress (Pa)	16	47	121	146	299	468
Plastic viscosity (Pa.s)	0.0130	0.0340	0.1073	0.1400	0.4716	1.1881

	Mixed Dump Material					
Percentage -75 μm	50%					
Slurry density (t/m^3)	1.40	1.50	1.60	1.65	1.70	-
Bingham yield stress (Pa)	27	79	207	328	520	-
Plastic viscosity (Pa.s)	0.0200	0.0613	0.2437	0.5644	1.5025	-

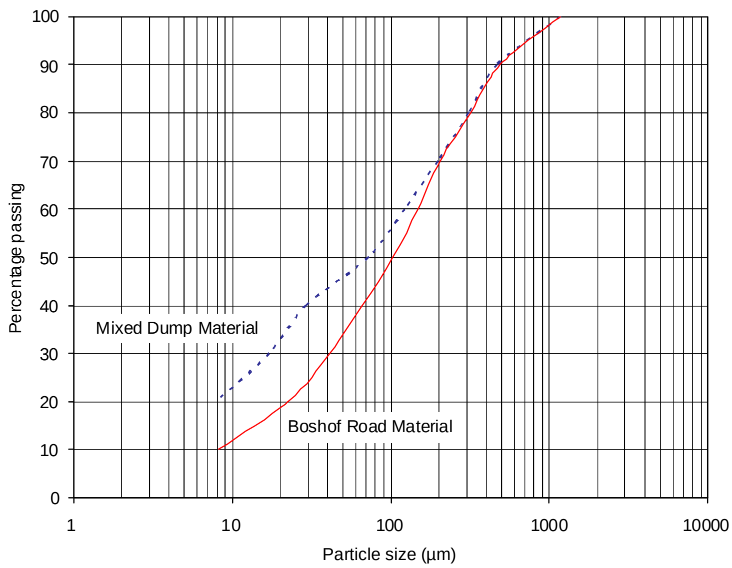

Figure 11.3 Particle size distribution

11.4.3 Particle settling

Because the pumping system was likely to be designed for operation in laminar flow, laminar flow settling tests were performed during the 2000 test programme under simulated shear conditions to determine the extent of grits settlement during the transit time in the pipeline. These tests indicated that the degree of grits settlement during the pipeline transit time was insignificant.

Although the tests indicated that at high densities there was no significant tendency for the coarse grits to settle in the pipeline, lower densities will occur occasionally during upset conditions and it is expected that some grits settlement will occur. The effective pressure gradient in the pipeline during normal (high density and high pressure gradient) operating conditions is greater than 2 kPa/m and any settled bed of grits will be kept in motion and cleared from the pipeline under these conditions. If the system is operated at low density and low pressure gradients, there is a risk of static settled bed formation leading to blockage. If periods of low density operation are unavoidable, it is important to increase the flow rate to prevent solids deposition.

11.4.4 Pipeline Hydraulic Design

A 330 mm internal diameter pipeline was selected taking into consideration pipeline and pump capital and operating costs, and the pressure gradient required for maintaining settled bed motion. The maximum pumping pressure for the highest percentage fines dump material at the maximum design tonnage is 12 MPa.

Figure 11.4 illustrates the design pumping envelope for a range of tonnages and densities. The system curve is very flat and is relatively insensitive to variations in tonnage or volumetric flow rate.

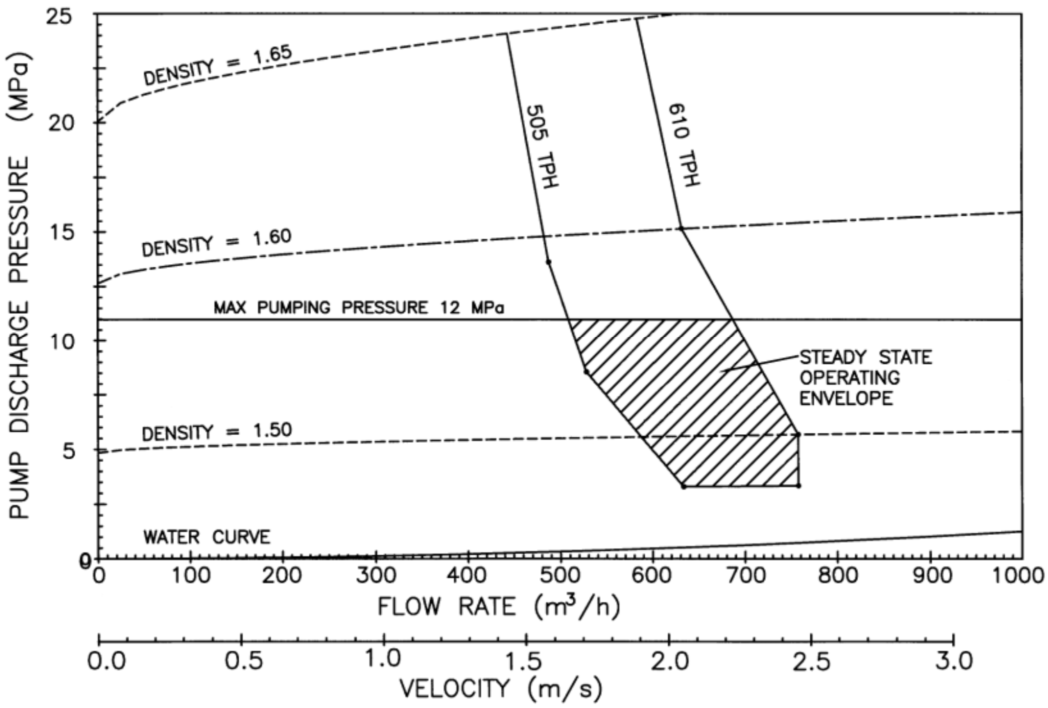

Figure 11.4 Pumping envelope

A detailed pressure transient analysis was performed for the full range of expected operating conditions and no significant overpressure conditions were predicted.

Corrosion and abrasion tests were conducted using representative slurry samples and a combined corrosion and wear allowance of 0.5 mm/year for the 10 year pipeline design life was adopted.

The ASME B31.11 Code for Pressure Piping for Slurry Transportation Systems was used to determine the pipe wall thickness and steel grade, and to check pipe stresses under sustained and thermally induced loads. Anchor thrust and pump discharge flange loadings were also determined from the stress analysis.

11.4.5 Thickener Underflow Consistency Control System

The flow behaviour of many slurries can be predicted by the density or percentage solids by volume. This is not the case for co-thickened kimberlitic slimes and grits slurries. Slurry density is very dependent on the percentage of grits whereas pressure gradient is strongly dependent on the percentage of rheologically active –75 μm particles in the slurry. For these reasons it was decided to use the pressure gradient in the thickener recirculation and underflow piping as the primary parameter for controlling the thickeners.

Pressure gradient and flow rate are measured in each thickener recirculation loop, each thickener underflow delivery pipeline and also in the main delivery pipeline. This data is used to obtain an indication of the pumpability of the slurry independently of slurry density and allows density to be maximised whilst ensuring that the slurry is still safely pumpable.

11.5 CONCLUSIONS

This paper presents a description of some of the design processes used in the selection of thickening and pumping equipment for a large kimberlite co-thickened slimes disposal system. Kimberlite can be problematic to thicken and pump at high densities because of the variable nature of the ore.

A careful study was made of the mineralogy and settling characteristics of the kimberlite ore types likely to be encountered during dump reprocessing in order to select the appropriate thickening equipment.

A unique control method has been employed to minimize the quantity of water required to dispose of the slimes without jeopardizing system reliability. The control system employs several tiers of protection to reduce the risk of pipeline blockage due to excessive slimes viscosity.

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