Coagulation of kimberlitic ore by gypsum

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De Beers Voorspoed Mine, South Africa

The thickening unit at De Beers Voorspoed Mine has historically been associated with over-consumption of thickening reagents, especially when treating problematic clay-containing kimberlite ore from deeper in the pit. The treatment of these ore types places extra pressures on the treatment plant, especially the tailings section. Clay-containing kimberlite ore necessitates pre-treatment by coagulation to achieve acceptable results in the thickening unit, which is a major cost driver for the plant. Gypsum was identified as a viable, more economical alternative coagulant. Industrial-scale test work was then performed by a two-phase trial, utilizing dry agricultural-grade phosphogypsum. These results showed a 19% saving on the overall cost of consumables and a 29% reduction in the thickener overflow turbidity. The gypsum retention time was shown to be 30.6 hours, reducing the dosage requirements for recycled water. Gypsum was implemented by Voorspoed mine as a process water conditioner due to these realized benefits.

INTRODUCTION

Background
De Beers Voorspoed mine is an open pit mine situated 30 km northeast of Kroonstad in the Free State Province of South Africa and is well known for the production of exotic coloured diamonds (De Beers Consolidated Mines, 2018). De Beers purchased Voorspoed mine in 1912, but only commissioned the processing plant in 2008 (Mining Technology, 2018). Voorspoed mine is a marginal mine, and therefore requires continuous business and process improvement in an attempt to optimize output and reduce operational costs.

The plant at Voorspoed mine has historically experienced high consumption of flocculant and coagulant when treating material bearing a high clay content, such as Rounded Xenolith-rich Volcaniclastic Kimberlite (RXVK) and Olivine-rich Volcaniclastic Kimberlite (OVK). Coagulation is required when treating these problematic material types to achieve satisfactory settling within the thickening unit. Alongside the high consumption of thickening reagents, poor operational performance was typical when treating these high clay content material types. Optimization work on the thickening unit led to an improvement in operational performance and overall consumption of consumables. Despite this, an increase in coagulant consumption was observed, resulting in the need for an alternative coagulant. Furthermore, as the pit at Voorspoed mine deepens, it is expected that a greater portion of the ROM feed will bear a high clay content, therefore necessitating more economic and efficient coagulants to be tested. Laboratory-scale test work completed in 2015 evaluated three coagulants as alternatives to the coagulant formerly used. Laboratory work commenced to evaluate alternative coagulants, which identified agricultural grade gypsum as a suitable alternative with an expected consumption of 8.75 kg/t (R3.85/t) versus the former coagulant consumption of 3.75 kg/t (R13.21/t), as well as improved settling rates.

It was therefore decided to implement plant-scale test work to evaluate the performance of gypsum as an alternative coagulant.
Voorspoed Processing Plant

The processing plant, as in Figure 1, has a design capacity of 4 Mt of run of mine (ROM) ore per annum. ROM ore treated by the plant typically consist of 70% Undifferentiated Volcaniclastic Kimberlite (UVK) material (bearing a lower concentration of clay), and 30% RXVK material (bearing a higher concentration of clay). The ROM material is screened and crushed to −185 mm by a jaw crusher, before being conveyed to the secondary crushing section. The primary crushing product is fed to a secondary screen, of which the screen oversize is conveyed to a cone crusher for secondary crushing (to −63 mm). The undersize material of the secondary screen is mixed with together with the cone crusher product and sent to the Fines Removal Plant (FRP).

The FRP consists of a high-capacity banana screen which removes the −1.5 mm fraction of the crushed ore. The remaining ore is conveyed to the crushed ore stockpile (COS). This −1.5 mm fraction is conveyed to the scrubbing section and split into 50% pre-scrubbing feed, and the remaining 50% is combined with the post-scrubbing material. Diamond liberation of the COS ore is accomplished by crushing to −40 mm with the use of a high-pressure role crusher (HPRC).

The HPRC product also reports to the scrubber for disagglomeration, which is followed by sizing into four streams. These material streams report to the DMS stockpile, coarse residue disposal (CRD) stockpile, the oversize material is recycled back to the COS, and finally the fine (<0.5 mm) material which reports to the thickening unit.

The DMS stockpile ore is firstly screened pre-classification, the underflow of which reports to the thickening unit, consisting of two 18 m diameter deep cone paste thickeners. The overflow is then treated in the DMS circuit, which produces three material streams: the DMS sinks which reports to the recovery plant, an oversize recycle stream sent to the COS, and the remainder of the material being conveyed to the CRD.

The slurry reporting to the thickening unit is thickened, the thickener underflow reporting to the fines residue deposit (FRD), and the clarified thickener overflow recirculating back to the process water tank for re-use by the plant.
A fundamental understanding of colloidal systems, coagulation, flocculation, and water and clay chemistry is required for effective water recovery optimization and the evaluation of gypsum as an alternative coagulant.

A colloid generally refers to a particle smaller than 1 μm and a dispersion of such particles is referred to as a ‘sol’. Dispersions of larger particles are referred to as suspensions; and both sols and suspensions can exhibit colloidal properties (Olphen, 1977). These suspended particles typically have a surface charge most commonly brought about by crystal lattice imperfections (Olphen, 1977). Generally, suspensions with a pH greater than 4 have a negative surface charge, with positive surface charges usually only occurring in strong acids (Holtham, 2006). These electrostatic forces create repulsion forces between like-charged particles which stabilize the suspension, thus preventing settling from taking place (Holtham, 2006). The absence of these electrostatic forces allows the particles to aggregate, by forming weak Van der Waals bonds (Concha, 2014).

Coagulation is the process of particle agglomeration by the addition of coagulants which destabilize suspensions by neutralizing the surface charge (Svarovsky, 2000), whereas flocculation achieves agglomeration of particles from suspensions by adsorption of individual particles onto large polymer chains (Concha, 2014). Kimberlite is known to produce a very persistent colloidal stable suspensions which have proven to be exceptionally difficult to dewater during the liberation process (Vietti, 2004). Generally, coagulation as well as flocculation of these suspensions is required for efficient solid-liquid separation by thickening (O’Gorman and Kitchener, 1974). Due to its characteristically low salinity and high pH values, non-settling kimberlitic ore behaves similarly to a subdivision of agricultural soils
termed non-saline alkali soils which belong to the greater group of the saline and alkali soils (Vietti, 2004).

In addition to the aforementioned characteristics, kimberlite ore typically contains clays, the most common being smectite and montmorillonite (Gilchrist and Hunt, 1988). Smectite clays are termed swelling clays due to their ability to absorb water and other polar molecules into the clay lattice. This swelling can cause a doubling in the volume of the solids in suspension (Grimm, 1968). These swelling clays typically necessitate coagulation to destabilize the suspended particles for efficient solid-liquid separation to occur (Vietti, 2004).

**METHODOLOGY**

**Plant Scale Test Work: Phase 1**

The initial phase 1 test work utilized 68 t of agricultural-grade phosphogypsum over a two-week period. The gypsum was pre-screened and crushed to ~10 mm by the providers. The addition of gypsum took place when treating problematic material types, such as RXVK. Gypsum was added to the water circuit in a dry state by hourly washing. Each batch of gypsum washed into the water circuit had a mass of approximately 1 t. Process water was used for the washing into the spillage pump. The pump used for this purpose was a vertical spindle pump (290 mm diameter impeller). The discharge of the spillage pump joins the feed to FRP screen, the underflow of which is pumped via a centrifugal 8/6 AH Warman pump to the scrubbing section of the plant.

The process water conductivity was monitored by taking hourly samples, which were analysed in the plant laboratory. This had to be done due to the lack of an online conductivity meter during phase 1 test work. The data was used to determine the retention time of the gypsum within the water circuit. This was done using Equations [1] and [2] below. An online turbidity meter was used to determine the effect of gypsum on the overflow clarity, which was indirectly used as an indication of the settling within the thickener.

![Figure 2. Addition of gypsum to FRP by washing.](image-url)
Furthermore, it is important to note that the coagulant pumps remained on automatic control during phase 1 test work in an attempt to avoid any unnecessary thickener related plant downtime.

Plant Scale Test Work: Phase 2
Phase 2 test work utilized 320 t of gypsum over a four-month period. The labour-intensive nature of the phase 1 test work called for alternative methods to be explored for the addition of gypsum into the system during phase 2. It was decided to add gypsum into the plant feed bin in a dry state, which was accomplished by the use of CAT 992 front-end loaders. Each batch of gypsum added into the plant feed had a mass of approximately 7.5 t.

The plant feed bin was chosen as it allowed for optimal time for the gypsum to be in contact with the process water circuit, thereby allowing optimal dissolution to take place. The first major source of agitation between the gypsum and the water circuit takes place within the FRP underflow pump, a centrifugal Warman 8/6 AH slurry pump. This pump transports 1150 m³/h of slurry at an average density of 1.05 t/m³ to the scrubbing section of the plant, as seen in Figure 1. Further mixing of gypsum and the process water takes place within the scrubber and the post-scrubbing screening underflow pumps which transport the slurry to the thickening unit.

This method of gypsum addition at the plant feed bin reduces the amount of contact between plant personnel and the gypsum, thereby reducing the risk associated with the inhalation of airborne gypsum particles. This risk was also mitigated by wetting the outside of the gypsum stockpile upon delivery, allowing the gypsum to form a crust which reduces airborne particles. The gypsum stockpile was situated such that it was surrounded by two earth bund walls, reducing the potential loss of gypsum due to handling or weather conditions.

Plant personnel were instructed to add gypsum as required. This requirement was determined by the clarity of the thickener overflow water. Gypsum was added to the system if the clarity was poor. Only half of a CAT 992 front-end loader bucketful was to be utilized per addition of gypsum, which equates to approximately 7.5 t of gypsum. Also, no more than two batches of gypsum were to be added to the system during a 24-hour period.

An online conductivity meter was installed and functional during phase 2 test work. This instrument was installed on a siphon pipe which drew process water from 1.5 m below the surface of the water in the thickener. It was assumed that both thickeners would have comparable conductivities as both thickeners receive feed from a common feed distribution tank. This data was used to determine the retention time of the gypsum within the process water circuit as well as the influence of the gypsum addition to the water circuit conductivity, measured in mS/cm per ton of gypsum added. The online turbidity meter was used to determine the effect of gypsum on the overflow clarity, which was indirectly used as an indication of the settling in the thickener.

RESULTS AND DISCUSSION

Plant Scale Test Work: Phase 1
Phase 1 work commenced on 18 January 2017 and ended on 1 of February 2017, with a total of 75260 t of DVK being treated, 56032 t of RXVK, and 7134 tons of Kimberlite-Basalt Breccia (KBBX), which will be grouped alongside RXVK as both material types exhibit similar behaviours within the thickening unit. Figure 3 depicts the daily tonnages treated by the plant, alongside the consumption of the commercial coagulant as well as the gypsum consumption, given in grams per ton.
As it can be seen in Figure 3, problematic material types such as RXVK and KBBX necessitate coagulation for acceptable settling and thickener overflow clarities. Average daily consumptions are discussed together with the associated costs in the cost comparison section.

When comparing Figure 3 and Figure 4, a definite correlation between poor overflow clarities is evident when treating difficult material types such as RXVK and OVX. Table I provides the daily average overflow turbidity per material during the phase 1 test work.
Table I. Phase 1: Daily average turbidity per material type.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Daily average turbidity (FNU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DVK</td>
<td>493</td>
</tr>
<tr>
<td>RXVK/KBBX</td>
<td>1783</td>
</tr>
</tbody>
</table>

The desired overflow turbidity set-point is 500 FNU. As seen in Table I, DVK achieved this clarity, whereas RXVK/KBBX did not. Despite not achieving the desired overflow clarity with this material type, these results do represent a 17% decrease in overflow turbidity as compared to the baseline (pre-gypsum usage) overflow turbidity for RXVK, which was 2159 FNU.

Process water typically has a conductivity of 1.5– mS/cm in the absence of gypsum. The process water conductivity for the phase 1 test work is shown in Figure 5. It is estimated that the conductivity increased by 0.039 mS/cm per ton of gypsum added to the water circuit. Acceptable overflow clarities were achieved within the thickening unit at conductivities within the range of 2.5–3 mS/cm during this period.

Cost Comparison
The baseline cost of thickening reagents are given in Table II. The baseline costs were determined from the average daily consumption per reagent per material type and this was subsequently converted to cost by the use of each reagent’s respective cost (in rands per gram reagent). The total cost was defined as the sum of the cost for flocculant, coagulant, and gypsum per ton ROM feed material treated by the plant.
Table II. Baseline reagent consumptions and costs.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Flocculant (g/t)</th>
<th>Coagulant (g/t)</th>
<th>Total cost (R/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVK</td>
<td>24.63</td>
<td>55.53</td>
<td>0.87</td>
</tr>
<tr>
<td>DVK</td>
<td>27.83</td>
<td>110.32</td>
<td>1.14</td>
</tr>
<tr>
<td>RXVK/OVK/KBBX</td>
<td>30.33</td>
<td>214.23</td>
<td>1.56</td>
</tr>
</tbody>
</table>

The operating costs for phase 1 are provided in Table III.

Table III. Phase 1: Consumption and operating costs.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Flocculant (g/t)</th>
<th>Coagulant (g/t)</th>
<th>Gypsum (g/t)</th>
<th>Total cost (R/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DVK</td>
<td>29.57</td>
<td>44.52</td>
<td>290.08</td>
<td>1.12</td>
</tr>
<tr>
<td>RXVK/KBBX</td>
<td>28.18</td>
<td>143.6</td>
<td>695.47</td>
<td>1.61</td>
</tr>
</tbody>
</table>

An overall increase of 0.4% in operational costs was realized during phase 1 test work. This negligible increase in operational costs alongside the 17% decrease overflow turbidity, necessitated extended phase 2 test work.

Plant Scale Test Work: Phase 2

Phase 2 test work commenced on 27 April 2017 and extended until 20 August. A total of 1 090 306 t were treated during this period. A summary of material types treated is given in Table IV. Material types are grouped according to the following groups: UVK, DVK, and RXVK/OVK/KBBX since RXVK, OVK and KBBX exhibit similar behavioural properties within the thickening unit.

Table IV. Phase 2: Material types treated.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Tons treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVK</td>
<td>274 178</td>
</tr>
<tr>
<td>DVK</td>
<td>622 346</td>
</tr>
<tr>
<td>RXVK/OVK/KBBX</td>
<td>193 782</td>
</tr>
</tbody>
</table>

Figure 6 depicts the coagulant and gypsum consumptions over the test period on a daily basis. The daily average consumption per material type is discussed in the cost comparison section. As the gypsum test work proved successful in reliably coagulating difficult-to-treat material types, the use of the commercial coagulant was stopped on 19 July 2017.
Figure 6. Phase 2: Material treated and reagent consumption.

The daily average overflow turbidity for the water recovery unit is depicted in Figure 7.

Figure 7. Phase 2: Daily average turbidity.

The daily average turbidity, as summarized in Table V, showed an improvement across all material types as compared to the daily average before gypsum usage. UVK improved by 20%, DVK by 12%, and RXVK/KBBX/OVK by 54%, thus an average overall improvement in overflow turbidity of 29%.
Table V. Phase 2: Daily average turbidity per material type.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Phase 2 daily average turbidity (FNU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVK</td>
<td>162</td>
</tr>
<tr>
<td>DVK</td>
<td>761</td>
</tr>
<tr>
<td>RXVK/KBBX/OVK</td>
<td>990</td>
</tr>
</tbody>
</table>

Poor overflow qualities were typically experienced at Voorspoed mine within the water recovery unit, most especially when treating problematic clay-containing kimberlitic ore such as RXVK or OVK. This is shown in Figure 8. Improving these overflow qualities was possible, although this came with considerable economic implications due to the high consumption requirements of the formerly used coagulant.

The use of gypsum as a process water conditioner to induce coagulation of the problematic kimberlitic ore has considerably improved the typical process water overflow quality. This clear improvement is shown in Figure 9.

Figure 8. Typical poor overflow quality.

Figure 9. Typical improved overflow quality.

Figure 10 depicts the daily average conductivity until 11 July 2017. Only intermittent data is available until the end of the test period due to instrumentation problems, which was incorporated into the dataset used for the determination of the gypsum retention time.
The process water conductivity at Voorspoed mine ranges between 1.5 and 2.0 mS/cm without the use of gypsum. While utilizing gypsum, the process water conductivity during the phase 2 test work period typically varied between 2.5 and 3.5 mS/cm, with peak conductivity reaching 4.5 mS/cm. The average gain in conductivity was 0.08 mS/cm per ton gypsum added to the water circuit, with a standard deviation of 0.03.

Gypsum proved to have a 30.6 hour retention time within the water circuit (estimated volume of 6400 m³), with a standard deviation of 15.3 hours. This further reduces the required dosage of gypsum to achieve sufficient coagulation within the thickening unit.

![Daily average conductivity](image)

*Figure 10. Phase 2: Daily average conductivity.*

**Cost Comparison**

The baseline operational consumptions and costs for the water recovery unit are set out in Table II. Costs were determined using the same methodology as that of phase 1 test work. Optimization work done within the water recovery section outside the scope of the gypsum test work has been factored out in the stated consumptions. The operating costs for phase 2 test work is given in Table VI per material type treated.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Flocculant (g/t)</th>
<th>Coagulant (g/t)</th>
<th>Gypsum (g/t)</th>
<th>Total cost (R/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVK</td>
<td>22.32</td>
<td>13.08</td>
<td>246.21</td>
<td>0.76</td>
</tr>
<tr>
<td>DVK</td>
<td>22.61</td>
<td>39.46</td>
<td>301.28</td>
<td>0.87</td>
</tr>
<tr>
<td>RXVK/OVK/KBBX</td>
<td>32.30</td>
<td>43.85</td>
<td>425.74</td>
<td>1.21</td>
</tr>
</tbody>
</table>

Table VII shows the average improvement in cost realised per material type treated during the phase 2 test work.
Table VII. Improvement in operational costs per material type.

<table>
<thead>
<tr>
<th>Material type</th>
<th>Improvement in baseline costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVK</td>
<td>12.98%</td>
</tr>
<tr>
<td>DVK</td>
<td>23.46%</td>
</tr>
<tr>
<td>RXVK/OVK/KBBX</td>
<td>22.57%</td>
</tr>
</tbody>
</table>

A comparison of these operational costs pre-gypsum usage to the operational costs realized in the phase 2 test work indicates an average decrease of 19.67% in total costs for consumables during the test period, which can be attributed directly to the use of gypsum as a coagulant.

**Downstream Benefits**

The underflow slurry from the thickening unit at De Beers Voorspoed mine is deposited on the FRD facility. Prior to the gypsum test work, the slimes deposited within the FRD facility would take several days to achieve settling for decanting, especially when treating problematic clay-containing ore. Since the implementation of gypsum as a process water conditioner, the slimes within FRD settle faster, requiring decanting almost on a daily basis at the penstock facility with a discharge of improved quality as shown in Figure 11.

![Figure 11. FRD penstock discharge (blue pipeline).](image)

A further benefit of frequent decanting is an increase in available freeboard, which decreases the risk associated with tailings disposal facilities.

**CONCLUSION**

The problematic clay-containing kimberlite ore at Voorspoed mine necessitates pretreatment by coagulation to achieve acceptable results within the thickening unit. The costs associated with this pretreatment were substantial, demanding optimization. Laboratory work indicated gypsum to be a viable alternative, which prompted the industrial-scale test work. Gypsum as a process water conditioner has been successful in reducing the associated costs of the water recovery unit by 19.67% and improving operational performance by 29%, while enhancing settling and decanting within the FRD facility.
REFERENCES


Ivan Frederick Kuit matriculated in 2011 at Hangklip High School in Komani in the Eastern Cape Province. He completed his Bachelor of Engineering in Chemical Engineering degree at the North-West University Potchefstroom campus in 2015. He started his career at De Beers Voorspoed mine in 2016 as a Metallurgist in Training, and in 2018 transferred to Anglo American New Vaal Colliery, currently under the new ownership of Seriti Resources, as a Senior Plant Metallurgist.