Port Durnford: clay mineralogy effects in a thickener

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The Port Durnford mineral deposit is situated south of the current Hillendale mine and extends for about 13 km southwards towards the town of Mtunzini on the east coast of South Africa. Port Durnford’s run-of-mine (ROM) material typically contains more than 20% slimes on a weight basis. As part of the feasibility study for this proposed project, thickening of the slimes was evaluated using a pilot-scale high rate thickener. Samples representing different material types found in the Port Durnford deposit were tested. Results showed that the thickener solids flux rates for Port Durnford material are lower than that of Hillendale, which is the current Exxaro mine on the South African east coast. Underflow densities achieved varied depending on the material type tested. The flocculant demand was also determined during the pilot campaign and the results compared well to actual consumption rates achieved at the Hillendale operation. For the overall slimes handling process to be successful the most important criteria for the thickening operation are the underflow properties achieved. The paper will therefore focus on the underflow properties achieved and show how clay mineralogy influenced the results obtained from pilot thickener trials.

Keywords: heavy mineral slimes, clay minerals, smectite, rheology.

Introduction

The Port Durnford mineral deposit is characterized by high slimes content, typically more than 20% of the expected run-of-mine (ROM). Slimes are defined in this case as material passing a 63 μm laboratory screen. This usually consists of fine particles and clay minerals, and it is the clay minerals that cause recovery losses at the primary gravity concentrator if not effectively removed (Marcos and Gilman, 2007). Once removed, the slimes need to be disposed of and water recovered for reuse in the process. A typical slimes processing route in a heavy minerals operation is to separate the slimes from the rest of the ROM by using hydrocyclones. The slimes would then report to the hydrocyclone overflow and further processed in a thickener. Very fine particles of a few microns in diameter settle slowly by gravity alone (Wills, 2007, Hayes, 2003). Chemicals, such as flocculants, are added to aid with agglomeration and settling of these particles in large diameter thickening vessels (Wills, 2007).

When one considers the feasibility of a mining project, the technical viability of the proposed process needs to be confirmed and relevant design information needs to be generated. For the evaluation of the proposed Port Durnford deposit the slimes handling process was one of the major cost drivers of the project. For this reason a pilot thickener study was undertaken to assist in the technical evaluation. The aims of the pilot campaign were:

• To confirm the ability to settle the Port Durnford slimes using available thickener technology
• To determine design information to enable the design of the thickener circuit and thus allow a detailed capital cost estimation of the required plant

• To determine operational parameters to allow consumption rates and thus operating cost to be determined.

In this paper a brief introduction of the important theoretical aspects that influence slimes behaviour during thickening are discussed—especially clay mineralogy since it influences thickening behaviour. The approach followed for the Port Durnford pilot thickening tests as well as results are discussed with the focus on how the clay mineralogy of the deposit influences the thickening performance. To conclude the implications on the slimes handling system are also discussed.

Theoretical considerations

Flocculants

Flocculants are high molecular polymers, mostly polyacrylamide monomers (PAM), which consist of significantly long chain lengths. The charge of the flocculant molecule can either be positive, negative or neutral. Due to the negative surface charge of clay minerals one would assume that cationic flocculants would show better results. However, the pH of the environment affects the surface charge of a particle. In an aqueous solution the hydroxyl group (OH) attaches itself to the edges of the clay particle (Svarovsky, 1981). In a solution with a low pH the acid will protonate the OH, leading to an overall positive charge. As the pH of the solution increases the OH deprotonates until a neutral edge charge is reached. A further increase in pH will result in an overall negative charge at the edges of the clay particle. The pH of the solution therefore strongly influences the flocculant charge that will be most effective. Apart from the pH influence, different clay mineral may also respond differently to specific flocculants.
Clay minerals belong to the phyllosilicate group—the crystal structures of minerals in this group consist of an arrangement of octahedral and tetrahedral sheets. Tetrahedral sheets consist of two planes of oxygen atoms arranged in tetrahedral coordination around Si4+ cations and share basal oxygen atoms between adjacent tetrahedral sheets. Octahedral sheets comprise six oxygen or hydroxyl ions which share octahedral edges. This type of linking results in a net charge of -2 which is balanced by divalent cations or trivalent cations that bond to the sheet (Horn and Strydom, 1998).

Clay minerals are defined as 1:1 or 2:1 clays. 1:1 clay minerals consist of a single octahedral sheet linked with one tetrahedral sheet. The linkage occurs through sharing of the apical oxygen between the octahedral and tetrahedral sheets. Two of the layers formed through the above mentioned bonding, link together through weak intermolecular forces (Horn and Strydom, 1998). The enclosed ion of each tetrahedron is normally Si4+, but this can be replaced by Al3+ or Fe3+. Water cannot enter between these layers and these clays are termed non-swelling clays, which include clays such as kaolinite and serpentine.

Clay minerals defined as 2:1 consist of a single octahedral sheet which is bordered on both sides by a tetrahedral sheet in which the apical oxygen point towards the central octahedral sheet. This forms one layer which can be linked to a similar layer through interlayer cations. The fact that the interlayer cations can be replaced by other cations is important as it relates directly to the ease with which these clay minerals can be chemically altered. The hydration of the interlayer cations results in the physical swelling of the clay minerals which could lead to the disintegration of the crystallite (also known as weathering) (Horn and Strydom, 1998).

Particle-packing relationship

The packing of particles on top of each other during settling influences rheology and density of the thickened underflow. The most familiar packing types are referred to as ‘edge–face’ also referred to as ‘house of cards’, and ‘face—face’ also known as a ‘band structure’ packing relationship (Van Olphen, 1977).

Figure 1 schematically illustrates this mechanism of flocculation. The length of the chain enables it to be partially absorbed onto the particle surface leaving the majority of the chain length to swerve around until it attaches to an adjacent particle. This leads to the formation of multi-particle aggregates also known as ‘flocs’ which settle out more quickly and easily. The longer the molecular chains, the faster the bridging between two adjacent particles can take place, leading to rapid floc formation and quicker settling (Moss and Dymond, 1978).

Once the flocculant and slimes are mixed and allowed to settle, the process of thickening begins.

Thickening and slimes disposal

Thickening or gravity sedimentation is the most widely applied dewatering technique in mineral processing. Relative to other dewatering processes, thickening is cost-effective and a high capacity process (Wills, 2007). Another advantage is that it involves very low shear forces, thus providing good conditions for flocculation of fine particles.

Two primary functions of a thickener are:

• Clarification of the overflow to enable reuse of water
• Thickening of the underflow to a required concentration (Wills, 2007).

The thickener overflow water is returned to the process water system for reuse in the process. The thickened underflow is disposed of typically in a residue disposal facility which allows for further dewatering. For the Port Durnford project, apart from the normal residue dam disposal, the reconstitution of soil using the thickened underflow and coarse sand was also a key consideration during the evaluation.

During rehabilitation efforts at the current Hillendale mine it has become apparent that slimes and sand need to be reconstituted to assure water retention of the soil and establishment of sugar cane production (Hattingh et al., 2007). For Port Durnford it is expected that the same rehabilitation method will be required as practised currently at the Hillendale mine. For both the disposal of thickened slimes in a residue disposal facility or for use to reconstitute soil, the underflow rheology is the main performance criteria. In the thickener pilot study for Port Durnford, the focus was on achieving the required underflow density as required for the rehabilitation process based on Hillendale rheology.

Clay mineralogy

Port Durnford material was analysed to characterize its clay mineralogy, since clay mineralogy can have a determining effect on the performance during the thickening process and subsequent disposal. From X-ray diffraction (XRD) analysis it was determined that the Port Durnford orebody is rich in clay minerals. In this document the term ‘clay’ is used as a mineralogical term, i.e. any of a diverse group of fine-grained platy minerals, not a size fraction. The negative surface charge, cation exchange capabilities, swelling characteristics and small particle size of clay minerals negatively affect the settling behaviour of the slimes fraction within a thickener (Van Olphen, 1977). These factors also affects the rheology of the slurry as it influences the solids concentration and the manner in which the particles stack during settling. The latter affects the rheology and consolidation behaviour of the slimes after deposition (Addai-Mensah, 2007).
Kaolinite typically stacks into a deck of cards structure, whereas smectite forms a honeycomb structure. Figure 2 illustrates this packing behaviour. The honeycomb packing retains large amounts of water which fills the voids formed by this type of arrangement (McFarlane et al., 2005a). Great effort and highly effective dewatering systems are required to remove the interstitial water (McFarlane et al., 2005a).

**Rheology**

Rheology is concerned with the flow and deformation of materials experiencing an applied force (Boger, 2006). There are several factors that influence the rheology behaviour of thickener underflow of which density, particle size, stacking relationship and the clay mineralogy seems to be the most important. The rheology of the underflow is measured in yield stress which refers to the stress at which the slurry starts to flow. Rheology is an important characteristic of the underflow as it determines how the slurry behaves during transfer to the deposition site as well as behaviour after it has been deposited. One of the deposition requirements for tailings disposal is that the yield stress is sufficiently high to support the largest particles which will ensure homogenous suspension where segregation does not occur (Boger, 2006). The non-segregating nature of the reconstituted soil for use in rehabilitation proposed for Port Durnford is the main performance criteria for the Port Durnford thickener design. The thickener pilot campaign thus focused on achieving the required underflow properties as required for the two disposal methods.

**Experimental**

Considering the theoretical background discussed, the pilot campaign was planned to generate the required information to assess the viability of slimes handling at Port Durnford.

**Quantitative X-ray diffraction analysis**

For this study all quantitative X-ray diffraction analysis was performed at the University of Pretoria. A PANalytical X′Pert pro powder diffractometer with X'Celerator detector and variable divergence and receiving slits with Fe filtered Co-Kα radiation was used. Quantification was performed using the Rietveld method (Autoquan Program).

**Yield stress measurements**

Yield stress (Pa) was measured using a Haake rheometer with a built in shear program. The vane design included 4 blades. Yield stress was measured and the peak yield stress was recorded for each measurement.

**Particle size distributions**

A Malvern Instruments Mastersizer was used to determine particle size distribution. The stirrer and ultrasonic mode were utilized. The particle refractive index setting was 1.53 and a 300RF lens was utilized. Water was used as a dispersant and the ultrasonic stirrer and other settings were kept constant for all tests.

**Sample selection**

The Port Durnford orebody is about 10 km long and around 4 km wide—at its deepest point it is in excess of 60 m deep. Due to the size of the deposit care had to be taken to ensure that all geological variations are considered when evaluating aspects such as thickening of the slimes fraction. As part of the geological evaluation of the orebody, extensive drilling was carried out and drill samples analysed to determine the valuable mineral quantities in the deposit.

Based on the lithological information generated by field geologists during exploration drilling, the orebody was divided into several sections. These sections, based on lithology, were further organized based on analyses done as part of the exploration process to define different material types found in the Port Durnford deposit. These material types were distinguished from each other by features such as typical slimes content, colour, sand sizing and response to magnetic separation on a Carpco magnetic separator. Based on experience at the Hillendale operation, it is known that differences in processing behaviour can be experienced when processing materials with variations in some of these features. The thickening pilot trial thus had to ensure that all material types present in Port Durnford could be successfully treated.

For the Port Durnford thickening pilot campaign, dedicated samples representing each of these material types were obtained using Wallis Air Core drilling at nominated positions in the deposit. Several drill samples of each material type were combined to obtain bulk samples. Water from the Hillendale plant was used as the proposed Port Durnford mine would use the same water source.

**Sample preparation**

As with Hillendale, the Port Durnford ore is shear sensitive. Figure 3 illustrates the shear sensitive nature of Port Durnford slime.
As energy is transferred to the slurry, more fine particles are generated which in turn influences the settling behaviour of the slimes. It was important to ensure that representative feed was prepared for the thickener campaigns. The mining process proposed for Port Durnford would include slurrying of the ore and pumping it significant distances before sand and slimes are separated in cyclones. Before feeding slimes to the pilot thickener, the slimes had to be exposed to a similar amount of shear to that expected during the actual mining process. To prepare the slimes for the thickener trials, a sump and cyclone set-up in closed circuit was used to ensure adequate and consistent shear to the ROM. The required time in the set-up to simulate the mining process was determined based on previous thickener campaigns conducted at Exxaro’s Hillendale mine. The assumption made for the Port Durnford pilot trial was that the mining process at Port Durnford would be similar to that of the current Hillendale mine.

**Thickener test set-up**

Figure 4 is a photograph of the pilot test thickener during installation. The thickener consisted of a 190 mm diameter Perspex vessel standing about 2 metres high with a feed well and rake mechanism.

The sheared and diluted feed slurry was introduced to the thickener unit at a controlled rate using a peristaltic pump. The feed density was kept constant for all tests at 1.012 kg/l. Flocculant was made up to a concentration of 0.1% by mass and then further diluted to 0.01% by mass prior to dosing to the thickener. Dosing was controlled by two peristaltic pumps which allowed two-stage dosing. The thickener feed lines had some inserted bends to aid mixing of the flocculant and feed. The thickener underflow was extracted using a peristaltic pump and discharged into a holding bucket for further testing and analysis.

**Thickener test program**

During the sample selection process six distinct material types were identified. For the purpose of this article only the two main types representing around 80% of the Port Durnford orebody are discussed. The two material types are referred to as type 2 and type 6. A sample from each of the material types of Port Durnford were subjected to the procedure as shown in Figure 5.

**Flocculant screening**

Prior to the thickener pilot study flocculant screening trials were conducted on a laboratory scale by flocculant supply companies. Static jar settling tests were conducted and settling rates achieved were recorded. The best performing flocculants based on the settling rates were shortlisted for further evaluation during the thickener pilot trial. The pilot thickener was run at fixed settings to evaluate the different candidate flocculants based on static jar tests. The flux rate,
Flocculant dosage and bed heights were kept constant for each flocculant trial and the underflow density was measured. The flocculant providing the best underflow density was selected.

**Flocculant demand**

Tests on the pilot thickener were run for each material type to determine the flocculant demand (optimum dosage rate). The bed height was built to 40 cm and the flocculant dosage rate (g/t) systematically increased. As the flocculant dosage increased the underflow was sampled and underflow density determined. The flocculant demand was taken as the rate at which any further increase in flocculant dosage rate had no further beneficial effect on the underflow. The flocculant demand tests were all run at a constant flux rate.

**Flux rate**

The thickener solids flux rate is measured in the units of tonnes/hour metre². For a fixed thickener set-up as used for the pilot trial the flux rate will be directly proportional to the solids feed rate. To determine the optimum flux rate for each material type the thickener was operated at a bed height of 40 cm and the underflow density determined for a set of flux rates. At low flux rates the underflow density is independent of the flux rate. As the flux rate increases a point is reached where further increases in the flux rate yields reduced underflow density. The optimum flux rate is defined as the point where the underflow density becomes a function of the flux rate. The flux rate is used to size the thickeners.

**Underflow density**

The final design parameter determined was the underflow density achievable. As the bed height in the thickener is increased the underflow density increases due to higher compression. The bed height was increased for each of the material types and the thickener underflow density measured at different bed heights. The terminal density is the density achieved where any further increase in bed height has no further impact in increasing the density. The terminal density that could be achieved would give an indication of densities that could be expected from an operational thickener. Apart from underflow density, the yield stress of the underflow was determined as it would influence the design of the raking mechanism. This was done by using the Haake rheometer. Both the rheology of the underflow as removed from the thickener as well as the rheology of the underflow following shearing was determined. This was done as underflow rheology changes with shearing. Generally the underflow yield stress will reduce following shearing. Figure 6 shows typical thickener underflow produced during the pilot campaign.

**Results and discussion**

The required design information for the thickener was generated based on the tests described. Flux rates were determined and these would serve as input to specify the thickener area required. The relative required thickening area for Port Durnford material was found to be larger than for material from the Hillendale deposit. Flocculant dosing rates were determined and compared well to those currently experienced at the Hillendale mine. The main focus of this paper is, however, the key design criteria for the thickening operation, which are the underflow properties from the thickener.

Figure 7 shows the relation between the underflow solids concentration in percentage and the bed height from the thickener trials for type 2 and type 6 materials respectively. On comparing underflow solids concentration as bed height is increased for the two material types, it can be seen that type 2 yielded higher solids concentrations than type 6. The rate of increase of solids concentration as bed height increases is also lower for type 6 material than type 2 material. This indicates that type 6 material does not dewater efficiently under the compressive conditions in a thickener bed.

In parallel to the pilot thickener campaign, clay mineralogy was investigated on the same samples to generate information to assist in the understanding of the material’s behaviour in processing. XRD analysis was used to define the clay minerals present in the different material types. Type 6 material was found to have high amounts (>35%) of the clay mineral smectite [Na₉₋₁₇(Al₃Mg₀.₇⁻).Si₅O₂₀(OH)₄.nH₂O]. Smectite is a swelling clay and absorbs various amounts of water thereby increasing volume and thus decreasing bulk density. As shown in Figure 2 the smectite tends to form honeycomb like structures that retain water (McFarlane et al., 2005a). The main clay mineral present for type 2 material was kaolinite (Al₂Si₄O₁₀(OH)₄), which typically has a low swelling capacity and is also the main clay mineral in the current Hillendale mine slimes fraction. The difference in clay mineralogy thus explains the difference in observed behaviour as shown in Figure 7.
The yield stress of the thickener underflow produced was also determined. Figure 8 gives the yield stress for both material types at different underflow solid percentages.

From Figure 8 it can be seen that the yield stress as a function of the underflow solids percentage has a similar relation with type 6 marginally higher at similar underflow % solids. A larger difference was, however, expected based on the differences as observed in Figure 7. The underflow tested and represented in Figure 8 was, however, tested as removed from the test vessel and the influence of the flocculant on the yield stress is expected to still be significant.

In practice the thickener underflow is removed from the thickener by pumps and pumped to the final disposal sites. The pumping operation shears the underflow leading to a loss in yield stress (for a shear thinning application). Figure 9 shows the yield stress and underflow percentage solids’ relation for the material tested following a shearing simulation. The rheometer had a built-in shear simulation program; after measuring the yield stress the vane would speed up for 10 seconds to shear the slurry after which the yield stress was remeasured.

From Figure 9 it can be seen that after shearing type 6 material has higher yield stress at similar underflow solids percentages compared to type 2 material. Figure 10 represents the pre-shear and post-shear yield stress for each test for the two material types.

Figure 10 shows that type 2 material exhibits a higher degree of shear thinning compared to type 6 material. This can be attributed to the high smectite content in type 6 material. In the swelled state, smectite occupies greater pulp volume, forming a high yield stress, water retaining gel structure (McFarlane et al., 2005a). McFarlane et al. (2005a) also concluded that the formation of honeycomb network structures that retain water also results in higher yield stress and opposes gravitational and shear induced compaction. McFarlane et al. (2005b) described how kaolinite dispersions flocculated with polyacrylamides (PAM) based flocculants deform when subjected to compression. The inter-flocculant porosity is also reduced, forming a higher pulp density following shear.

It can thus be seen that for type 2 material higher underflow solids concentrations can be achieved with corresponding high yield stress. Following shearing, the yield stress of type 2 material will, however, be reduced. For type 6 material the thickener will not be able to produce high underflow solids concentrations. Subsequent yield stress will typically also be lower than the high solid concentration underflow when treating type 2 material. Type 6 material will, however, maintain its as thickened yield stress following pumping operations yielding a higher yield stress at the point of disposal than for type 2 material of similar solids’ concentration.

The objective for the thickener tests was to achieve high underflow densities that would allow maximum flexibility for downstream disposal processes. The proposed Port Durnford project would dispose of slimes on a sub-aerial residue dam as well as a bulk mix with sand for dune coating. For the bulk mixing process, the requirements to achieve high densities and yield stress in the thickener underflow are more stringent than for the residue dam disposal. The residue dam’s pumping system incorporates dilution facilities which enable it to handle high thicker underflow densities and yield stress. The successful disposal dam as well as bulk mixing operation is, however, dependent on the thickened slimes rheology more than on the underflow density. There are significant differences between the behaviour of type 2 and type 6 materials as determined from the pilot thickener campaign. The higher yield stresses achieved for type 6 following shear compared to that of type 2 at similar densities can, however, possibly offset the lower thickener underflow solid concentrations achievable with type 6 material compared to type 2 material. This would thus possibly lead to both material types, even though behaving differently in the thickener process, being successfully disposed of via the two disposal routes.

Figure 9. Yield stress as a function of underflow solids percentage measured following shearing

Figure 8. Yield stress as a function of underflow solids percentage measured as discharged from the thickener (unsheared)

Figure 10. Comparison of yield stress achieved before and after shearing for each of the material types
Conclusions
From the pilot thickener campaign the required design information was generated to confirm the suitability of high rate thickening for treating Port Durnford material. The investigations revealed marked differences in thickening behaviour between the material types tested for Port Durnford. It was shown that these differences are primarily due to differences in clay mineralogy. Since the rheology of the thickened slimes will determine the downstream disposal behaviour, follow-on studies will have to be done to confirm the performance of the material types in disposal processes.

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References

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