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High density slurry and paste tailings, transport systems

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High density slurry and paste tailings systems offer significant environmental benefits primarily related to reduced water consumption. However, these potential advantages need to be evaluated on a project-by-project basis.

The successful design of a thickened or paste tailings system requires that the system is designed to accommodate the effect of the high density slurry on pumps, pipelines and the overall system operation. The transport system must be designed as an integrated unit and the interaction of all the components need to be considered. The transport system includes the slurry preparation plant, the pump station and the pipeline.

This paper assesses the impact of increasing the slurry density in a platinum tailings system from conventional densities to thickened and paste tailings densities. As slurry density and rheology increase, there is a sharp increase in energy consumption for the additional water savings and this additional cost needs to be considered. A case study shows that there is a considerable benefit in increasing densities to the point at which tailings can be still be deposited in the standard manner.

For existing systems, increasing density can result in an increased capacity at a marginal power cost, provided that the slurry is not too viscous. For a new system, a smaller pump and pipeline can result in lower capital costs and a marginally higher energy cost, if the optimum density is selected.

Keywords: tailings, paste, pumping, slurry

Introduction

There is an urgent need to minimize water consumption by the mining industry both locally and abroad, driven by environmental and legislative requirements. This is especially true in South Africa where the expansion of existing platinum operations and development of new platinum mines in arid areas is placing increasing demands on water resources. Consequently, there is great deal of interest in high density and paste tailings, disposal systems and they certainly offer many potential advantages that need to be considered on a site-specific basis. Substantial water savings can be achieved by increasing the solids concentration of the slurry disposal system.

There is a continuum in slurry flow behaviour from conventionally thickened slurries to paste slurries, as shown in Figure 1 (Jewell *et al*, 2002). At some value of solids concentration, the effect of yield stress and viscosity increases significantly and the behaviour changes such that different thickening equipment is needed, or disposal techniques are affected; however, pumping requirements are still moderate. Further increases in solids concentration begin to have an exponential effect on material properties and the viscous properties dominate. At this point, the material becomes more 'paste' like and the processing and pumping become more complex. Finally, the solids content approaches a filter cake and can no longer be pumped.

This relationship is true for most mineral slurries; however, the point at which the behaviour changes varies considerably and the engineering challenge is to determine the optimum solids concentration for the specific system. There is a level at which the overall economics of the project can no longer justify the increased capital costs associated with specialized pumps and thickeners, or the higher running costs, due to the high pumping pressures.

Definitions

Paste is a very descriptive term that is more qualitative than

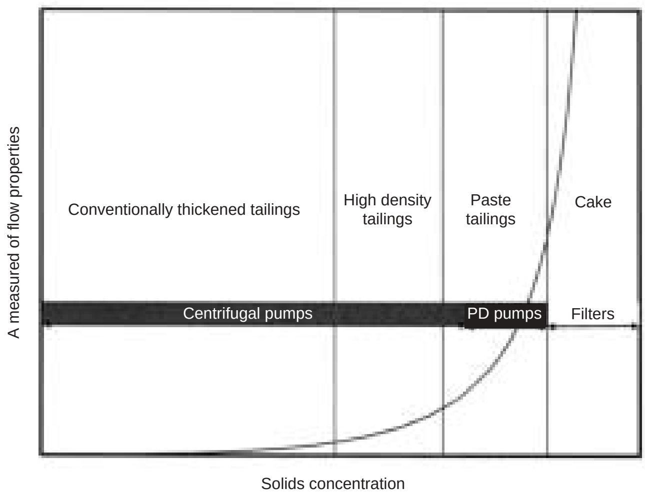

Figure 1. The thickening continuum: flow behaviour versus solids concentration

quantitative, as visually one can identify a paste-like substance from a less viscous substance. Unfortunately in reality, there is no clear distinction between a thickened high density tailings and a paste slurry. From a pipeline flow perspective, it is necessary to understand the changes in flow behaviour as solids concentration increases and it is not always necessary to define the slurry as thickened or a paste tailings. The same applies to the preparation and disposal requirements. It is nonetheless, important to provide some broad definitions to define some of the principal characteristics.

High density

High density slurries are typically slurries where the solids are uniformly distributed across the pipe section and there is no vertical concentration gradient (Cooke and Paterson, 2004). If the material is relatively fine, the solid and liquid phases may not separate until a long period in a quiescent state has passed. These slow or non-settling slurries are also called homogeneous slurries. Non-settling fine slurries often exhibit non-Newtonian behaviour i.e. a non linear relationship between shear stress and shear rate. Laminar flow occurs at low velocities and flow becomes turbulent at high velocities. Pipe friction is dominated by the viscous properties of the slurry. Once the material is deposited, there is some bleed water and water can be recovered from the disposal facility.

Paste mixtures

Paste refers to high concentration slurry that is generally produced using a combination of vacuum or pressure filters, thickeners, cyclones and mixers. Filters are used to maximize the water recovery. Paste mixtures may have binders added to them to increase their strength if they are used for underground backfill.

Paste also requires a reasonably high fines content to provide adequate non-Newtonian properties. Typically, a minimum requirement is that the particle size distribution must have at least 15% of the particles finer than 20 μm. Paste materials have very high frictional losses and can be transported at low velocities without particles settling on the pipe invert. On deposition there is very little, or no, bleed water from the mixture and no water is recovered from the disposal site.

Design considerations

Systems approach

Increasing solids concentration has a number of requirements that are different from a conventional slurry system. Designing a high density system requires an overall systems approach as there is strong dependence between the disposal site requirements, pumping requirements and preparation facilities.

A typical example that illustrates this is that high density systems are often considered, when additional storage capacity is needed for a given site geometry. Typically the storage capacity of a disposal site can be increased, due to the greater beaching angles achieved with a higher solids concentration slurry, as illustrated in Figure 2.

The beach slope achieved on a deposition site is a combination of many factors, such as deposition rate, terrain slope, particle size grading, layer thickness, drying cycle etc., but one of the key parameters is slurry yield stress (Sofrà and Boger, 2001). Slurries with high yield stresses tend to deposit at steeper angles than slurries with a low yield stress. It is necessary to establish the slurry properties in terms of size grading, viscosity and yield stress that will result in the necessary beaching slope to achieve the storage capacity. Once this is established, the process requirements to produce the high density slurry must be investigated, together with the pumping requirements to transport the more viscous material. If the required storage capacity cannot be achieved without a high beaching angle, then alternative disposal sites need to be investigated. Close co-operation is needed between the different engineering disciplines to ensure that the preparation facility can produce a sufficiently thick material that will form the required beaching angles after it has been transported from the preparation site to the disposal facility.

Increasing solids concentration affects the following preparation and pumping processes:

- Slurry preparation requirements to achieve consistently viscous material
- Hydraulic design of the system, which is more complex due to variable rheology
- Mechanical design of the piping components due to higher operating pressures
- Pump selection criteria between centrifugal and positive displacement pumps.

These are discussed briefly below:

Slurry preparation guidelines

High density tailings systems require specialized thickening equipment, normally with increased physical height to allow the formation of a deeper mud bed depth and to increase mud bed retention time. High rake torque is produced by the deep viscous mud bed, and heavy duty rake structures and drive mechanisms are required.

Underflow density control

Whether the motivation is water savings or reduced deposition facility costs, it is important to reliably maintain the density and rheology of the thickener underflow within a fairly narrow operating range. Excessive densities may result in viscous pipeline blockages and low densities may cause erosion damage or instability problems at the deposition site. In the case of certain tailings slurries containing coarse particles, the slurry flow properties are not directly related to density and some form of rheology measurement may be required to maintain suitable deposition site slope angles.

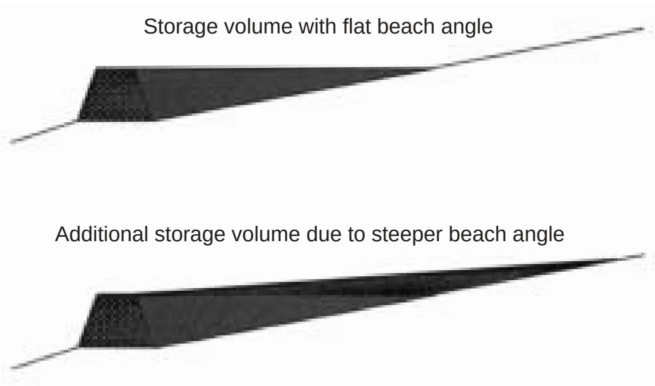

Figure 2. Additional storage volume due to increased beaching angle

Control system integration

Thickeners are generally supplied as turnkey vendor packages that include design, fabrication, erection and commissioning. It is important that the thickener and pumping system designers co-operate from the start of the project, to ensure that the systems are compatible. Most new mineral processing plants will be controlled by a central supervisory system that provides an operator interface and automatically controls all equipment sequences and control loops. The control systems of both the thickeners and the pumping system must be developed in parallel and incorporated into the central supervisory system to meet the requirements of the overall system control philosophy.

Hydraulic design issues

High pipeline pressure gradients

The exponential increase in yield stress and viscosity as solids, concentration increases is a common feature of high density systems. This means that these slurries will have higher pipeline pressure gradients than conventional tailings slurries and pump station discharge pressures may require the use of positive displacement pumps.

Careful design is required to select the optimum solids, concentration and pumping pressure, that will minimize overall system capital and operating costs. A realistic assessment of the water savings and envisaged environmental and closure benefits need to be done as part of the engineering trade-off study.

Minimum transport velocity

Minimum transport velocity is one the fundamental criteria upon which conventional settling slurry pumping systems are designed. In many high density systems, there is no measurable particle settling under design conditions and the selection of a suitable operating velocity presents the designer with a considerable challenge. The pumping systems can, in many cases, be designed to operate in laminar flow, if the non-settling nature of the slurry can be confirmed, by test work, for all anticipated operating conditions. Normally, this requires high pipeline pressure gradients to provide sufficient force to slide a settled bed of solids. This is easily achievable in small diameter pipelines; however, high volume thickened tailings systems require large diameter pipelines and laminar settling can be a problem, as has been reported in several pipelines that operate in laminar flow (Cooke, 2002).

Centrifugal pump head and efficiency de-rating

At the higher viscosities at which these systems operate, substantial head and efficiency de-rating become an important design issue. Pump selection and motor sizing must always take de-rating into account. In certain cases, the reduction in centrifugal pump performance, due to viscosity de-rating, is sufficient to justify the use of positive displacement pumps, which are not affected by this de-rating.

Pump considerations

Centrifugal pumps will be adequate for medium density systems with short pipeline lengths, whereas positive displacement pumps will be required for high density systems with long pipelines. For intermediate systems, both centrifugal and positive displacement pump options must be investigated to find the most cost-effective solution over the design life of the system.

Centrifugal pumping systems generally offer lower capital costs but higher operating costs than a positive displacement pumping system of similar capacity. Multistage series centrifugal pump stations are generally limited to discharge pressures of approximately 4 MPa. If the required pumping pressure exceeds this value, booster stations along the pipeline or positive displacement pumps are required.

Positive displacement pump valves will be blocked, or damaged by tramp material larger than a certain size, typically 6 mm. Provision must be made in the system design to intercept this material before the pump. Screening of the dilute thickener feed is possible but requires high capacity screens and does not intercept objects, such as bolts or welding rods, that often fall into the thickeners during maintenance. Self flushing in-line screens can be installed on the thickener underflow pipelines but a reliable system will require careful design.

Large positive displacement pumps have delivery times of up to 12 months and this must be taken into consideration in the selection process

Pipeline considerations

The main areas where high density and conventional tailings pipelines differ, are related to operating pressure and wear rate. High density slurry pipelines often operate at a higher pressure than conventional tailings, pipelines and pipeline mechanical design must take this into account. In some cases, the pipelines operate at much lower flow velocities than conventional tailings, pipelines and are subject to reduced wear rates.

Conventional tailings, pipelines are typically flanged at 12 m intervals to facilitate unblocking and replacement of worn lengths. High pressure pipelines are often constructed of continuously welded piping without flanges, in order to save costs and to reduce the risks of flange leaks. This approach is only practical where the risk of settled solids blockages is low and where pipeline wall thickness reduction, due to corrosion and erosion is expected to be low.

Tailings, pipelines are commonly installed above ground and are subjected to large thermal expansion movements, especially in the case of long straight piping runs. The stresses generated by these movements must be limited by careful design, particularly in the case of high pressure pipelines. A pipeline stress analysis is recommended for pipelines operating at pressures above 2 MPa, where appropriate.

Case study

The above engineering requirements are driven by the selection of the solids, concentration of the tailings, system. In some instances it is necessary to produce very thick paste tailings and in these cases it is a 'non-negotiable' requirement to produce paste tailings. However, in many instances it is possible to achieve a substantial water saving at a reasonable cost, by assessing the affects of solids concentration on the pumping requirements and selecting an optimum trade-off between preparation, pumping costs and water savings.

This will be demonstrated by considering the effect of solids concentration on a typical platinum tailings system.

Effect of solids' concentration

South African platinum tailings, slurries are comprised mainly of Merensky or UG2 reef. The flow behaviour of each tailings type, on each mine, varies according to particle size grading, solids concentration and rheology. The typical range of particle size distributions of Merensky and UG2 tailings in the Rustenburg region, are shown in Figure 3. Extensive test work has been conducted on a wide range of tailings from various platinum mines in South Africa and the following general pipe flow observations can be made:

- At low densities, i.e. conventional tailings systems, both slurries behave as settling or mixed-regime slurries.
- Merensky:
  - become increasingly non-Newtonian in behaviour above slurry densities of approximately 1.70 to 1.80 t/m^3.
  - is more viscous than UG2 at high slurry densities.
- UG2 tailings:
  - flow behaviour changes above densities of approximately 1.90 to 2.0t/m^3.
  - is finer than Merensky; however, it settles faster due to a higher solids density.
- Both UG2 and Merensky tailings require high transport velocities to prevent solids depositing on the pipe invert, even at high solids, concentrations.

Current practice is to dispose of platinum tailings at densities of between 1.50 to 1.55 t/m^3 using conventional spigot systems. Densities can be increased to approximately 1.70 t/m^3, without significantly affecting the pumping requirements and conventional disposal methods can probably still be used. At higher densities, the tailings exhibit paste properties and the cost of preparation and pumping becomes significant.

The affect of slurry density (solids concentration) on the pumping energy requirements is illustrated by considering the change in flow behaviour from 1.55 to 1.70 to 2.10 t/m^3 for a Merensky tailings system (Mine A). Table I presents the typical slurry properties for Merensky (Mine A) and UG2 tailings (Mine B) at these densities. In this case, the Merensky tailings will probably exhibit paste flow behaviour at densities of 2.10t/m^3, whereas UG2 still has a fairly low yield stress and will behave as a thickened tailings.

System analysis: Mine A

Platinum operations typically use several operating pipelines in parallel to transfer tailings to the disposal site and 250 mm nominal diameter pipelines are fairly common.

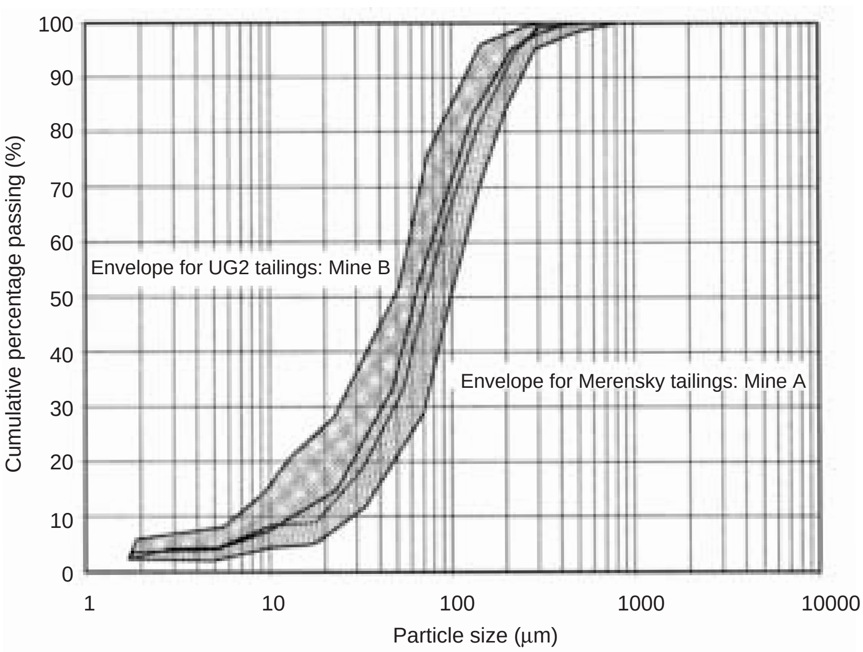

Figure 3. Typical UG2 and Merensky tailings particle size distribution

Table I
Comparison of Merensky and UG2 Tailings

Parameter	Mine A: Merensky			Mine B: UG2		
Slurry density (t/m^3)	1.55	1.70	2.10	1.55	1.70	2.100
Solids' density (t/m^3)	3.15–3.24 (3.20 average)			3.47–3.51 (3.49 average)		
Solids' concentration	51.6%m	59.9%m	76.2%m	49.7%m	57.7%m	73.4%m
Solids' concentration	25.0%v	31.8%v	50.0%v	22.1%v	28.1%v	44.2%v
Mean particle size, d_{50}	65–100 μm			50–70 μm		
Bingham yield stress	1.51 Pa	4.55 Pa	102.53 Pa	1.05 Pa	3.06 Pa	45.41 Pa
Plastic viscosity	0.0046 Pa.s	0.0088 Pa.s	0.4093 Pa.s	0.0041 Pa.s	0.0071 Pa.s	0.1162 Pa.s
Flow regime	Conventional	Thickened	Paste	Conventional	Thickened	Thickened

Assuming typical values, let us consider the effect of solids concentration on the pipeline diameter and energy consumption for a 250 mm pipeline system transporting 350 dry tons/hour of the Merensky tailings from Mine A.

Pipeline flow behaviour

Figure 4 shows the calculated pipeline pressure gradient in a 250 mm internal diameter pipeline. The following should be noted:

- *Point A*—The original design conditions are selected to ensure that the transport velocity is greater than the deposition velocity during normal operation. The slurry flow rate is 438 m^3/h. The flow is turbulent
- *Point B*—As slurry density increases to 1.70 t/m^3, the flow rate decreases to 344 m^3/h and the pipeline velocity is less than the deposition velocity. The flow remains turbulent; however, there is a risk of pipeline blockage
- *Point C*—At 2.10 t/m^3 the flow rate is 219 m^3/h and the flow is laminar. As the pipeline pressure gradients are greater than 2 kPa/m, the risk of blockage is low, even at low velocities.

At a slurry density of 1.70 t/m^3 the velocity is too low and it is necessary to either:

- Install a smaller pipeline diameter to increase the slurry velocity, as shown in Figure 5, while maintaining a constant mass throughput of 350 tons/hour. This shows that, for a new system a smaller pipeline and pump set could be used.
- Increase the pipeline throughput, as shown in Figure 6, to ensure that the velocity is greater than the deposition velocity, by:
  - increasing plant capacity
  - operating the system intermittently, using the thickener or sumps for the required surge capacity
  - decreasing the number of pipelines in operation, only if several pipelines in parallel are used for the total tailings stream.

In this example it is possible to increase the 250 mm pipeline capacity by 20% from 350 to 420 tons/hour by increasing slurry density from 1.55 to 1.70 t/m^3 or greater.

Specific energy consumption analysis

For a particular mass throughput there is an optimum pipeline diameter and density that will result in the lowest specific energy consumption (SEC). The SEC is the energy in kilowatt-hours to move one ton of solids a horizontal distance of one kilometre. It is calculated from:

$$SEC\ (kW.h/t/km) = \frac{g i_m}{3.6\ S_s\ C_v}, \qquad [1]$$

where g = acceleration due to gravity (m/s^2)
i_m = mixture head loss (m water/m)
S_s = solids' relative density
C_v = solids' concentration by volume.

The SEC is determined for a constant tonnage in a given pipe diameter as density or solids' concentration varies. Figure 7 shows the change in SEC as density varies using different diameter pipelines transporting 350 dry tons per hour at different densities. For each pipeline diameter, the minimum SEC occurs at the transition, from laminar to turbulent flow. In this instance, it is not possible to operate at these velocities, as the solids will settle on the pipeline invert. For each pipeline diameter shown, the point at which deposition occurs is shown. At densities less than these values, the velocity is above the deposition velocity and at higher densities, the velocity is too low.

Analysis of the SEC relationship in a 250 mm pipeline shows that the density can be increased from 1.55 to 1.60 t/m^3 and the SEC will decrease. However, to transport 1.70 t/m^3 tailings, a smaller 225 mm pipeline is needed.

Figure 7 also shows that the maximum density that can be achieved without significantly increasing the specific power consumption is approximately 1.75 to 1.80 t/m^3 in a 225 mm pipeline. At higher densities, the flow becomes laminar and SEC increases dramatically.

This analysis does not consider the increased reduction in pump performance as viscosity increases and does not allow for overall pump efficiency. It is very likely that when the effect of solids on pump performance is included, there will be further increases in the energy consumption at the densities above 2.0 t/m^3.

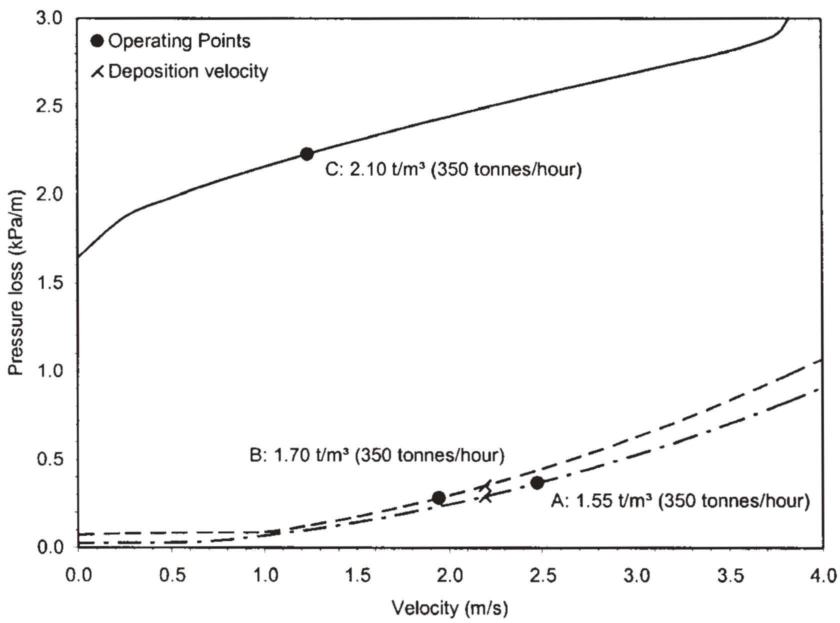

Figure 4. Flow behaviour of Mine A Merensky tailings: pipeline diameter = 250 mm

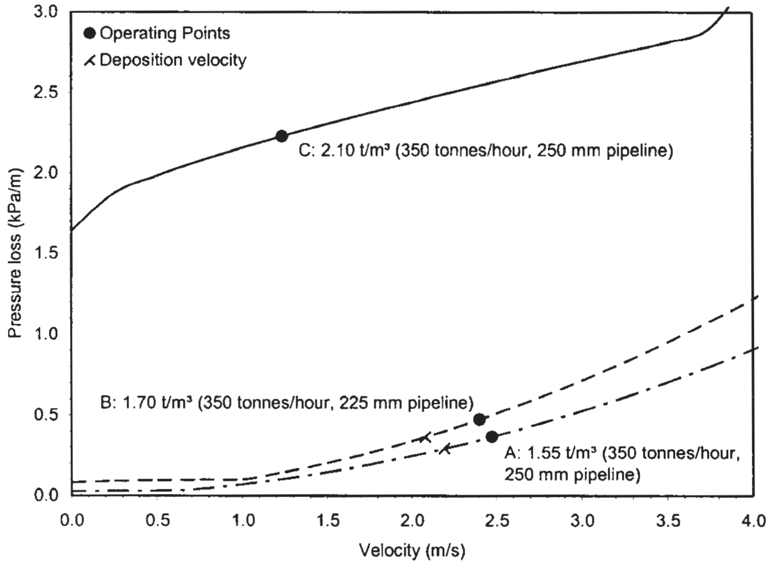

Figure 5. Flow behaviour of Mine A Merensky tailings: varying pipeline diameter

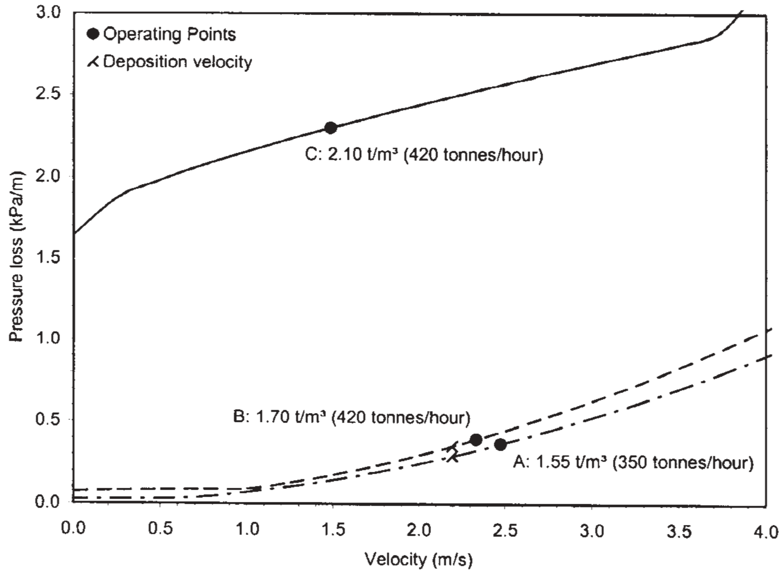

Figure 6. Flow behaviour of Mine A Merensky tailings: pipeline diameter = 250 mm

Decreasing pipeline diameter (350 tons/hour)

If the pipeline diameter is decreased as density increases and the tonnage remains constant (as shown in Figure 5), then increasing density from 1.55 to 1.70 t/m^3 results in an additional 0.008 kW.h/km for each additional m^3 of water saved; however, further increasing density to 2.10 m^3/t requires an additional 0.722 kW.h/km for each m^3 of water, as seen in Table II.

Increasing pipeline capacity (250 mm pipeline)

The energy consumption for the operating conditions shown in Figure 6, are summarized in Table III. The associated incremental water saving and additional energy required per m^3 of water is also shown. This shows that less energy per m^3 water/ton solids is consumed as density increases from 1.55 to 1.70 t/m^3. However, increasing density to 2.10 t/m^3 requires an additional 0.817 kW.h/km for each m^3 of water.

This analysis shows that the most energy efficient combination at 420 tons/hour throughput occurs in a 250 mm pipeline at a density of approximately 1.70 t/m^3 and that there is a diminishing benefit to increase densities further.

Conclusions

This paper highlights some of the important engineering issues that need to be considered when designing or implementing a high density tailings system. Most importantly, the analysis of the effects of solids' concentration on the pumping energy requirements for a typical South African platinum tailings, systems has shown:

- Current systems that operate at densities of 1.50 to 1.55 t/m^3 can transport slurries with densities up to 1.70 t/m^3 with an improved overall energy consumption per ton solids.

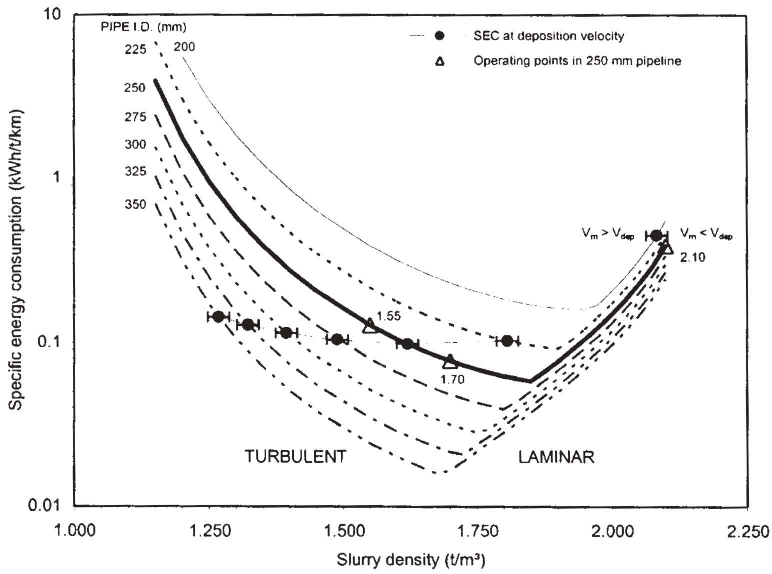

Figure 7. SEC as a function of slurry density at 350 tons/hour mass throughput (Mine A Merensky tailings)

Table II
Energy consumption per tonne solids (constant tonnage, varying diameter)

Density (t/m³)	1.55	1.70	2.10
Capacity (tons/hour)	350	350	350
Slurry flow rate (m³/h)	437.5	343.8	218.8
Water flow rate (m³/h)	328.1	234.4	109.4
Internal diameter (m)	0.250	0.225	0.250
Pressure gradient (kPa/m)	0.365	0.473	2.229
Water consumption per ton solids, excluding water return dam water savings (m³/t)	0.938	0.670	0.313
Net change (m³/t)	–	0.268	0.357
Specific energy consumption (kW.h/t/km)	0.127	0.129	0.387
Net change (kW.h/t/km)	–	0.002	0.258
Additional energy required per m³ water saving (kW.h/km)	–	0.008	0.722

Table III
Energy consumption per tonne solids (increasing pipeline capacity)

Density (t/m³)	1.55	1.70	2.10
Capacity (tonnes/hour)	350	420	420
Slurry flow rate (m³/h)	437.5	412.5	262.5
Water flow rate (m³/h)	328.1	281.3	131.3
Internal diameter (m)	0.250	0.250	0.250
Pressure gradient (kPa/m)	0.365	0.394	2.300
Water consumption per tonne solids, excluding water return dam water savings (m³/t)	0.938	0.670	0.313
Net change (m³/t)	-	0.268	0.357
Specific energy consumption (kW.h/t/km)	0.127	0.107	0.399
Net change (kW.h/t/km)	-	-0.019	0.292
Additional energy required per m³ water saving (kW.h/km)	-	-0.073	0.817

- It is possible to increase throughput or capacity in low density systems by increasing solids concentrations without a major impact on the pumping requirements.
- Significant water savings can be achieved at nominal additional energy costs, by increasing the density of existing tailings systems to 1.70 t/m³.
- At the same mass throughput, smaller pumps and pipelines can be used to transport platinum tailings at densities of 1.70 t/m³ than at 1.55 t/m³, thereby reducing capital cost.

The above findings will vary according to individual mine tailings, mineralogy, size grading and rheology. A detailed analysis of the implications of increasing density on the disposal facility need to be included.

By doing an appropriate analysis of the system, the optimum combination of diameter and density to maximize the water saving and energy costs can be determined.

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