RHEOLOGICAL AND DEPOSITIONAL CHARACTERISATION OF PASTE-LIKE TAILINGS SLURRIES

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Abstract
The rheological and depositional character of tailings from two base metal concentrators are presented based on results obtained in connection with pilot-scale thickening tests and feasibility considerations. Thickening to a volumetric solids concentration of over 45% (70% by mass) close to the disposal area results in a non-segregating slurry that can be deposited at average slopes of 3-4%. Operating literature data from installations are briefly described and some macroscopic depositional mechanisms and design features are discussed.

1. Introduction
The feasibility of a high degree of tailings slurry thickening and deposition at angles of 3-4% is determined by the possibility to fill more volume per unit surface area, thus limiting water holding dam facilities and areas that need to be rehabilitated. The solids concentrations by volume must often exceed 45% which means slurry properties that gives a conceptually even slope with no segregation of particles and virtually no drainage of water. The term paste is used in a slightly loose way here, it was originally associated with bauxite residue storage and tailings backfilling in underground mines. The local conditions strongly determine the technical-economical feasibility and environmental effectiveness of different degrees of thickening and surface disposal.

With a paste system circulation of large quantities of water through the disposal area can be avoided. Water availability may be a critical issue in arid or semi-arid areas where water exposed in the disposal area is largely lost through evaporation. In sub-arctic and arctic regions heat recovery with rapid water circulation through thickening can improve the energy effectiveness in the mineral processing, see for example Hollow et al. (2007), Oxenford and Lord (2006).

Disposal of tailings at high solids concentrations often means unsaturated conditions with susceptibility to oxygen exposure in the comparatively small tailings storage areas. Aspects related to deposition management schemas and the adoption of multi-layer capping for tailings containing various degrees of AMD-generating minerals will not be covered here. General aspects and experiences of using paste deposition for AMD-generating tailings can be found in Jewell and Fourie (2006).
2. Objective and scope.

The objective is here to briefly characterize the rheological and depositional behaviour of two tailings products based on test work and feasibility considerations at LKAB’s Svappavaara concentrator and at MultiServ AB’s slag recovery plant. The aim is also to present some depositional data from installations described in the literature and to discuss some macroscopic depositional mechanisms.

The depositional characterization is mainly a summary of results presented in Engman et al. (2004), where laboratory and field work are described in details together with results from the thickening pilot-scale trials. The rheological characterization is based on results from pipeline flow in small-diameter hoses and flume flows (Engman et al. 2004) and pipeline loop pumping experiments in diameters from 0.060 to 0.2 m, Wennberg and Sellgren (2007). Details on various considered equipments for thickening and pumping are not covered in this study.

3.1 Svappavaara

In the Luossavaara-Kiirunavaara AB (LKAB) concentrator in Svappavaara close to the arctic circle about 0.7 Mtonnes of dry tailings per year (90 tonnes/h) is transported nearly 1 km as a slurry in parallel pipelines connected to a flume discharging into a tailings pond. In order to limit the cost of tailings management in the existing area surface disposal of a highly thickened slurry is considered. The need for costly dam rises in the disposal area are mainly avoided with thickened disposal. The most attractive location of the thickener is on a hill close to the disposal area (Wennberg and Sellgren, 2007), see Figure 1.

![Figure 1. Schematic sketch of the two alternative locations of the high-density thickener at the LKAB Svappavaara concentrator.](image-url)
3.2 MultiServ AB
In the company's plant in central Sweden for recovery of metal slag about 0.23 Mtonnes per year (50 tonnes/h) are planned to be thickened in the disposal area about 500 m away from the concentrator. The thickened tailings will, depending on location of the thickener, then be pumped 50 to 500 m to the disposal area, see Figure 2.

Figure 2. Schematic sketch of the disposal area at MultiServ AB in central Sweden.

During the first years of operation the existing disposal area will be covered with paste. This means a covering of the disposal with simplified rehabilitation and also reduced leaching from the deposit. In addition the ground water table will be lowered in the existing deposit before the final tight seal capping.

The use of paste disposal has been chosen due to economical, environmental and safety issues. The location in a valley downstream an existing deposit has been seen very favourable for a paste system. The final location of the thickener has not yet been decided, but due to high costs for paste pumping a location and the edge of the existing deposit is seen as the best option. According to a newly received permit for the metal recovery operation including the deposition and storage system, the paste system must be in operation before the end of 2009 and the new deposit latest 2014.

4 Characterization
Various design features related to the paste thickening, pumping and placement are in the literature normally related to the rheology of the highly concentrated mineral particle-water mixture, especially the yield stress. The yield stress is defined as the minimum stress required causing the solid-liquid mixture to flow. The standard “slump” method for consistency measurements in the concrete industry has been adopted and modified for paste-like tailings slurries, see for example Jewell and Fourie (2006).
Early experiences of surface deposition and handling at very high solids concentrations often comprised bauxite processing, i.e. clay minerals. Tailings from the diamond and oil sand industries often also deal with active clay minerals. High clay content normally has a strong effect on the rheological properties of the tailings slurry. For ground rock base metal mine tailings, the finer (clay-sized) particles are not really clay minerals but rock flour, Fourie (2002), a dissimilarity also marked by Robinsky (1999). Recent work with slurries of the type considered here has shown that they may not behave in a completely non-settling way flowing homogeneously during transportation, see for example Pullum (2007).

For simplicity, the characterization of the flow behaviour during transportation is here adopting the generally accepted rheological parameters to describe the flow resistance of homogeneously flows of paste-like tailings slurries.

4.1 Depositional characterization

The discharge from the pilot-scale thickening tests at both plants were with 0.025 m-plastic hoses, at MultiServe with discharge in a trench with bottom width of 1.5 m and height about 1 m. The deposition observations at the Svappavaara concentrator took place on a horizontal floor with created cones with diameters of 7 to 8 m and heights of 0.5 to 1 m. In addition, batch tests were carried out in a flume with width, height and length of 0.2, 0.1 and 1.5, respectively. The various laboratory and field set-ups and detailed results are given by Engman et al. (2004), a summary of deposition slopes are shown in Figure 3.

![Figure 3](image_url)

Figure 3. Observed deposition angles from 0.025m diameter discharge pipelines and batch flume tests. Unfilled and filled marks correspond to the tests at LKAB and MultiServ AB, respectively. Solids density 3000 kg/m³.

Circulated in Figure 3 is coupled to tests with agitated slurry through a circulating pump arrangement in the lower portion of the thickener. It was observed that this slurry flowed more easily down the slope. It follows from Figure 3 that average slopes of 10 to 15% were obtained from a volumetric concentration of about 45% and that pump circulation in the thickener at MultiServ AB tended to lower the slope, thus affecting the behaviour of the slurry.
4.2 Rheological characterisation

Observations of continuous flow over a length of about 1 m in a flume with width and height 0.2 and 0.1 m, respectively, were carried out at slopes from about 12 up to 27% where approximately uniform conditions with a nearly constant depth were observed. No deposition of particles were observed. The corresponding analysis for estimation of average shear stresses is given in details by Engman et al. (2004).

The wall shear stress, $\tau_w$, for the free surface flow in a flume or in a pipeline is related to the pressure gradient, $\Delta p/\Delta x$, and the friction loss gradient, $j$, in m slurry per m through the following relationship:

$$\tau_w = \frac{(\Delta p / \Delta x)D}{4} = \frac{pgjD}{4}$$

where $\rho$ is the slurry density. $D$ is here the hydraulic diameter which corresponds to the pipeline diameter for flow in a filled pipeline section. For the free surface flume flow, $D = 4A/P$ where $A$ is the average section area and $P$ is the average wetted perimeter.

Summarized pipe and flume wall shear stress results (Eq. 1) versus a viscous scaling parameter, the bulk shear rate, $8V/D$ ($V$ is velocity), are shown in Figure 4 covering pipeline diameters of 0.025 and 0.05 m. Similar results are shown in Figure 5 for separate larger pipeline diameter tests with Svappavaara-tailings. With large diameters, it was not possible to do on-site large-scale pipeline pumping tests at the time of pilot-scale thickening tests because of low paste production rates. Consequently, the tests were carried out with stored and re-mixed pastes.

![Figure 4](image-url)
The results in Figure 4 were based on indicative measurements (Engman et al. 2004) and the accuracy of the data in Figure 5 were discussed in some details by (Wennberg and Sellgren (2007). The uncertainties expressed in Figures 4 and 5 may to some extent express the variability in practice, related local slurry properties and thickener operation. A perspective on the results in Figures 4 and 5 may be represented by evaluated wall shear stresses of 500 and 20 Pa corresponding to concentrations of 50 and 40%, respectively.

5. Some case studies

Operating data focused on depositional conditions are briefly described based on information given by Jewell and Fourie (2006) and Oxenford and Lord (2006). Solids concentrations by mass are given within parenthesis together with the volumetric values.

The Kidd Creek mine and processing operations in central Ontario in Canada have a well functioning thickening facility since 1995 where underflow at a concentration by volume, C, of about 35% (62.5%) is pumped 1100 m in centrifugal pumps to a centrally located discharge point. The average slope is 2.5 to 3 % and the average particle size, $d_{50}$, about 20 µm and the solids density 3100 kg/m$^3$.

Surface disposal of paste was chosen to extend the life of the Myra Falls mine at the Pacific coast of British Columbia in Canada. A combination of tank thickening with a portion dewatered further in filters gave an average C-value of 36% (67%) The max. particle size was about 100 µm and $d_{50}$ about 12 µm with 20% smaller than 10 µm. Solids density=3600 kg/m$^3$. Transportation with PD-pump with down-valley discharge resulted in a average slope of about 3%.

In the Cabriza gold-copper mine in Peru about 200 t/h tailings are thickened to about 45% (75%) in a deep cone thickener. The slurry becomes non-segregating at about 41% (70%). Solids density 3700 kg/m$^3$ and $d_{50}$ from 15 to 25 µm. Deposition from a pipeline laid out along a hillside with 10 spigots each about 0.1 m in diameter. Centrifugal pumps used so far, positive displacement pump installed for extended pumping lengths.
The copper-gold Osborne mine operations in Australia produces about 200 tonnes/h of a tailings product with 10% less than 20 µm, d<sub>50</sub> about 70 µm and max. particles of 1 to 2 mm. Average solids density= 3500 kg/m<sup>3</sup>. Deposition from an elevated central discharge point means an advancing cone of deposited tailings. Full scale trials showed that average slopes of 1.1 and 2.5% were obtained for C-values of 26 (55%) and 35% (65%) respectively, when deposited conventionally. A C-value of 42% (72%) was required for segregation-free deposition and a slope of 4% was obtained for 44%(73%)

The Century zinc mine in Australia uses down-valley deposition for about 500 tonnes/h. The intention here was not to go for the steepest slope for the tailings with d<sub>50</sub>= 12µm and solids density 2820 kg/m<sup>3</sup>.A high rate thickener increased the C-value to about 30%(55%) giving slopes of 1% and 0.6% in the upper and lower portions of the disposal area, respectively, which was considered sufficient here.

6. Deposition mechanisms
6.1 Conventional deposition
In conventional low concentration tailings slurry discharge from a pipeline or flume in the disposal area, the slurry flow takes place in self-forming meandering channels as the particles deposit along the surface (“beach”). Segregation of the coarser and finer particles occurs with coarser particles settling out close to the discharge point with finer particles being transported further along the beach. The location of the channels change over time and the detailed local directions is driven by gravity along the path of least resistance. The cross-sectional shape of a channel that forms in underlying deposited tailings is a mechanism that cannot be considered to be fully understood, ASCE (1998). The free surface flow often ends at an open water surface (pond), where remaining fine particles settle out under water.

The continuously decreasing inclination of the deposited tailings beach profile normally results in a slope that is less than 0.5%, due to the fine particle content. Many attempts have been to generalize this upward concave profile into a “master profile, see for example Blight (1994). He found that beach concavity is mainly caused by the particle sorting.

As an alternative to one tailings slurry discharge point, multiple discharges from a main pipeline through short pipelines mounted perpendicular to the main pipeline (spigots) are used. Spigoting in low to medium concentration tailings handling results normally in an increased sorting effect with coarser particles building up close to the discharges along the perimeter of the confined embankment, thus contributing to its function. Thus, spigoting means an increased initial slope, however, the downstream value normally attains the low slopes typical for one-point discharge.

The experience with spigoting giving a higher average slope for a given flow rate and solids concentration when split up in several discharge points with lower flow rates expresses the ability of a large flow rate to cause the flow channels to adapt a flatter slope thus bringing the deposition farther out along the beach.

Generally with conventional handling at a constant discharge flow rate, the effect of hindered particle settling through increased volumetric solids concentration also brings the deposition farther out. For example, a slurry of narrowly graded particles of about 100 µm in average size will be transported about 50% longer distance before settling out for an increase in solids concentration from 10 to 30% (CUR 1992). The effect on the average slope is here not obvious because the resistance to flow may be higher for the 30%-mixture.
A discharged tailings slurry characterized by very small particles, for example clay, can be considered to flow homogeneously, i.e. like a viscous fluid. No settling out of particles will take place and an increase in the clay content increases the viscous behaviour and the flow resistance, corresponding to a larger slope for a constant flow rate. Large flow rates for a constant concentration enable the slurry to gradually spread further, thus influencing the average slope.

6.2 Thickened tailings deposition
Williams (2001) suggest that two flow regimes exist on a tailings beach related to the flow of highly-concentrated tailings slurries. A slurry stream in a narrow confined channel with turbulent flow transports the tailings slurry to a localised broader area where the flow attains sheet-like laminar flow where particles settle together, so-called zone-settling. This is recognised at the main mechanisms for profile formation. Laminar conditions cannot persist and with the local slope steep enough, turbulent flow will be maintained in the self-formed channel. Cyclic repetition along the beach will in this way determine a limiting equilibrium slope in a macroscopic sense, Pirouz et al. 2005 and Pirouz et al. (2007).

7. Discussion and conclusions
Recent approaches for slope evaluations, for example by Pirouz et al. (2007) and others, may provide a means of predicting the beach slope angle with tailings slurries of arbitrary rheological characterisation. The reported findings explain to some extent the difficulty with laboratory scale flume tests, because of the problem to obtain turbulent flow conditions.

An alternative to a rheologically-based slope modelling approach is now considered and limited to slope scaling predictions related to the turbulent settling behaviour of particles with sizes of about 100 µm, De Groot et al. (1998)

The channellised tailings flow equilibrium slope concept discussed above with a net settling out of tailings is here related to the slope requirement for a balance between sedimentation and erosion along a beach formed by dredging material from parallel discharges from several large pipelines, De Groot et al. (1988). They investigated slope angles for various narrowly graded fine sand medium concentration slurries with particles down to about 60 µm, i.e. two-component “settling” type of mixtures. They showed how the slope is dependent not only on the particle size but also on the discharge flow rate, with steeper slopes for lower discharge rates. They quantified the results from small- and large-scale flume experiments and field observations in an empirical relationship (CUR 1992), which here expresses the slope, $S_m$, obtained for modelled (small) flow rates, $Q_m$, and larger prototype flow rates, $Q_p$, as follows:

$$\frac{S_p}{S_m} = \left(\frac{q_m}{q_p}\right)^{0.45}$$

where $S_p$ is the prototype slope and $q_p$ and $q_m$ are defined as $Q_p/B_p$ and $Q_m/B_m$, where $B_m$ and $B_p$ are characteristic widths between discharges. The formulation in Eq.(2) is now adopted assuming discharge in two parallel and closely located pipelines both in the model and prototype scale, each with diameter $D_m$ and $D_p$, respectively. The solids concentrations in Figure 3 for which the slopes start to increase are related to the discharge from 0.025 m pipelines from the pilot-scale thickening tests. This diameter is taken as the pipe diameter, $D_m$ in Eq.(2), with $D_p$ of the order of 0.1-0.15 m and values of $Q_m$ determined by the capacities.
The estimation expressed in Eq.(3), briefly used by Engman et al. (2004), indicates that disposal slopes for the applications considered here should be about 2.5 to 4% because observed slopes during the tests were 10 to 16%, dependent on the circulating pump was operating or not (Figure 3).

Robinsky (1999) presented a series of laboratory-scale flume deposition slope results together with the corresponding particle size distributions. Comparisons with the observed slopes of 10 to 20% here confirm roughly the results by Robinsky for similar size distributions also giving field slopes of about 4%. However, he did not explicitly express any scale-up criterion. Simms (2007) found that the 1:4 estimation in Eq.(3) was reasonable in a comparison with a rheological approach for slope estimations and scaling. Evaluation of flume data with field observations in the study by Pirouz et al. (2007) indicated a ratio close to 1:2.

The indicatively quantifications discussed here on how small discharge rates tend to give higher slopes demonstrate flexibility possibilities for the long term management of the tailings storage facility. Spigoting, or simply a split of the pipeline flow into two streams just before the discharge end would be feasible, principally giving two discharge points. However, there are reasons to use only one pipeline to transport thickened slurry over long distances, because the pressure (energy) requirement increases with a decreased pipeline diameter.

Conceptually with pastes, the deposited tailings has a planar slope, i.e. no concavity. Experiences to date indicate that some degree of concavity occurs For example, the deposition scheme at Kid Creek described above has a slope concavity of about 2.5 m on a radius of 1000m from a central discharge point. It is important to consider this effect in a long term design perspective. Significant densification (consolidation) and deposit strength results often from natural evaporation in warm areas and through freeze-thaw cycles in cold regions. For example, the entire in situ deposit at the Kidd Creek disposal area described earlier is consolidated to near the shrinkage limit at C about 56%, corresponding to a density of 2175 kg/m³. Simms (2007) related compaction effects to cyclic deposition schemes also giving steeped slopes.

With the small amount of water reaching the disposal area with the highly thickened tailings an increased potential for dust generation can be expected compared to conventional deposition. However, it has been suggested that the lack of segregation with better packing should make the surface more resistant to wind erosion, as indicatively demonstrated in a laboratory-scale comparison by Robinsky (1999). The total surface area exposed to the wind may also be limited, especially if a central discharge system is avoided.

The elevated location of the paste-thickener on the ridge close to the disposal area in Figure 1 are considered to be layered as paste in the vicinity of the thickener over several years and then after about 20 years with pipeline lengths of up to 900m. During the first years of operation only one thickener underflow pump is required. The reliability and performance for various pump configurations and depositional schemes are planned to be investigated systematically in order to meet the most effective long-term solution for paste thickener operation, pipeline distribution and placement in the disposal area as the discharge point advances over the life of the project.
8. References

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