Paste technology for tailings management

T. Meggyes and Á. Debreczeni

Abstract
Tailings are the fine-grained residue of the milling process in which the desired raw materials are extracted from the mined rock, and, due to mixing with water during this process, appear as slurries. The deposits of these residues in ponds or lagoons, usually confined by man-made dams, can present a serious threat, especially where there is improper handling and management. Technologies which use the sub-aqueous conventional upstream, centreline and downstream methods have left a legacy of many unstable tailings facilities with potentially liquefiable zones and steep slopes which are prone to erosion. The technology of producing high-density, very low-moisture thickened tailings, i.e. paste technology (PT), has made rapid progress from 1995 onwards, and offers significant economic incentives and environmental benefits. No particle segregation takes place during the thickening process; the paste material exhibits a much greater stability than conventional tailings; there is no pond on top of the deposit; the paste forms a gently sloping surface after placement which promotes the runoff of rain water; and the overall costs are lower than for conventional methods. Due to these features, PT, in many cases, offers a highly advantageous disposal technology, providing stable deposits and a reduced risk to humans and the environment. In certain cases, dry stacking, which has many similar advantageous features, is preferred. Concrete applications should be assessed on a case-by-case basis.

Key words: milling, paste technology, slimes, slump, slurry, tailings, tailings disposal, tailings facilities, tailings ponds, thickened tailings, ultra-high-density 'paste' thickener, ultra-high-rate thickener, yield stress

INTRODUCTION

The basic differences between conventional tailings disposal and PT are:

- In the conventional tailings disposal system the tailings properties are fixed by the processing plant and all confining dykes and ‘control structures’ have to be engineered to withstand the stresses imposed on them by nature.
- In the PT system the tailings properties are ‘engineered’ to suit the unstructured natural topography of the disposal area – a much safer and more environmentally friendly approach.

By the process of thickening the tailings to a heavy slurry prior to disposal, it is possible to create a self-supporting deposit of tailings and to eliminate the typical superimposed settling pond (Robinsky 1999). The reason why the failure of a conventional tailings disposal dam is so environmentally disastrous is not the dam itself, but the fact that the dam retains a mass of very loose unconsolidated tailings and a great deal of process water. If the dam fails, the contents liquefy completely as they flow through the breach. In this liquid state, they can flow many kilometres downstream, as happened in the Stava, Italy, catastrophe in 1985, where 250 000 m$^3$ of liquefied tailings rushed down the Stava Valley following a dam breach, achieving a peak velocity of 90 km/h and burying two villages and claiming 268 lives, making it the worst tailings facility disaster ever to have occurred in Europe (Chandler and Tosatti 1995).

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TECHNOLOGY BASICS

The reason that the material is so loose in the first place is that it has been discharged into a pond filled with water. The tailings particles drift down through the water, their weight reduced by 50% due to buoyancy, to form a loose structure, like a ‘house of cards’ or lake-bottom mud. It does not take much of a shock to collapse the material into a liquefied state.

The aim of PT is to create a self-supporting ridge or hill of tailings, and thus to minimize the requirement for confining dams. To achieve this the tailings must be strengthened, which can be done by the removal of most of the process water. This is attained by passing the tailings that include process water through high-density thickeners (large circular tanks) wherein the tailings particles settle to the bottom and are extracted as underflow for release into the disposal area. Most of the process water is taken off the top and recycled back into the plant. The thickening process must be sufficient to change the tailings and process water from a mixture to a non-segregating, but still pumpable, slurry. For some tailings, it may be necessary to filter part of the underflow and recombine the filtered solids with the remaining underflow to attain the desired consistency.

When the tailings are released, due to their heavy consistency and thus high viscosity they will flow great distances without segregation. Eventually the flow stops at a gentle slope. The slope is controlled by the degree of thickening. The aim is to attain a slope of 2% to 6% (1.1 to 3.4°) in moderate climates. Such slopes are sufficiently gentle to avoid erosion, yet provide good drainage for vegetation. In very dry conditions even steeper slopes may be contemplated. The non-segregating property of thickened tailings is also responsible for bonding the tailings particles and thus reducing both erosion potential and dusting.

Tailings disposal areas may consist of valleys or flat terrain somewhere in the vicinity of the processing plant. To form a sloping tailings deposit in a valley, the thickened tailings would be discharged at the head of the valley or along one of the side hills. The heavy slurry will flow down the valley until it encounters a slope flatter than its own, or alternatively, until it is stopped by a small dam. On flat terrain, thickened tailings would be discharged from an artificial ramp or tower, resulting in a ridge or cone of tailings (Figure 1).

Only a low perimeter dyke is required to direct precipitation and a small amount of extruded process water to a pond, ideally located beyond the limits of the tailings deposit, for recycling. Due to thickening, such a pond will receive only one-third of the amount of process water that flows to conventional ponds.

It is the homogeneity of the slurry (the result of thickening) and the gently sloping surface of the tail-

Figure 1. Paste disposal from an artificial tower. Note the gently sloping surface (Newman 2003; Engels 2003)
ings that provide the major advantages of the PT system over conventional flat, wet disposal areas. During the active life of the disposal area, as well as after closure, the surface of the sloped tailings drains rapidly, and allows drying to take place. One of the aims of the system is to provide sufficient surface area during deposition to allow drying of the discharged tailings, thus strengthening them considerably. The elimination of the conventional pond on top of the deposit also provides a major environmental advantage: the hydrostatic head that causes seepage of process- and rain-water to occur throughout conventionally deposited tailings is eliminated. Another very important environmental advantage is that no confining dam(s) are needed or, at least, they are reduced substantially in height.

Finally, the adoption of the system may permit progressive reclamation in some topographical settings – a feature that permits the close-out of one end of the disposal area even as the discharge is moving progressively towards the other end. This advantage may result in a much smaller active disposal area. If a mine is abandoned for any reason, most of its disposal area would have already been reclaimed. Progressive reclamation may reduce the assurance bond demanded in some jurisdictions to guarantee eventual reclamation of the area after closure. A test on 68 tailings and processing plants from all over the world proved that all would satisfy the requirements for PT. The materials tested included tailings from gold, silver, copper, zinc, bauxite, phosphate, tar sand, diamond, etc. Conversion from conventional to thickened tailings disposal can be realistically achieved for any existing tailings operation. Discharging a sloping tailings cap on an existing conventional flat tailings disposal pond will facilitate reclamation. The alumina industry fighting the problems of red mud disposal is probably the most forward-looking industry by adopting PT to a large number of tailings facilities.

The capital cost of thickening for a PT system should be weighed against the cost of constructing and operating a conventional disposal system, including the final reclamation costs (Robinsky 1999).

PT also inhibits acid drainage. The best way of doing this is to keep sulphides in a saturated condition, thus preventing them from coming into contact with oxygen. The homogeneous slurry of thickened tailings due to the fines promotes high matrix or capillary suction that raises water near the surface and keeps the tailings saturated.

Paste is a high-density mixture of water and fine solid particles. It has a relatively low water content (10–25%), such that the mixture has a consistency as measured by the ASTM slump cone test from slightly greater than zero up to nearly 305 mm (12 in). Particles of different size classes will not segregate or settle when the paste is not being agitated or when it is stationary in a pipeline, i.e. the paste has no critical velocity. Cement may be a component of the paste. Larger particles of aggregate can be added to a paste without greatly changing the pipeline transport characteristics (Brackebusch 1994).

The moisture content or density of a paste for a given slump consistency depends on the size distribution of the particles. The finer the particles, the more surface area must be wetted. This yields higher moisture contents and lower densities for a given consistency. With larger particles, the surface area is smaller and this results in lower moisture content and higher density.

Having a sufficient amount of fine particles is the most important requirement to produce a paste. In most cases, pastes must contain at least 15% by weight of particles less than 20 µm in diameter (625 mesh) (Tengeren 2000). Mineralogy and particle shape affect the amount of fine particles necessary (Slottie and Schreiber 1999).

As experience has shown that it is difficult to scale up paste flow characteristics from small-scale tests to full-scale pipeline conditions, pilot-scale pumping tests are usually necessary. PLC-control is essential because only slight changes in moisture content cause wide variations in viscosity and pipe friction.

Figure 2 shows a classification system for solid–liquid mixtures (Jewell 2002). In terms of increasing concentrations of solids, slurry is followed by paste and then by cake. A yield stress range of 200 ± 25 Pa is proposed as marking the transition between slurry and paste. A transition from slurry to paste may occur as the mixture flows down a slope from the discharge point and releases excess ‘bleed’ water. This happens with tailings derived from hard rock ores where the clay-sized fraction (< 2 µm) is primarily composed of granular-shaped particles. These tailings would cease flowing once the self-weight forces on the solidifying
Tailings from a milling operation are usually discharged as a dilute slurry. Excess water may be recovered for recycling in the milling operation by a tailings thickener. Therefore, dewatering of the tailings slurry is usually the first step. Fine particles, ‘slimes’, must not be lost during the dewatering operation. A conventional gravity thickener becomes the equipment of choice for the first stage of dewatering. If more than a sufficient amount of fine particles are present in the tailings stream, part of the stream can be processed with a hydrocyclone and the overflow discarded, thus removing some of the water and increasing the thickening and filtration rates. This is called partial classification (Brackebusch 1994).

Key factors affecting thickening and clarification of a feed stream (Bedell et al. 2002) are:

- solid–liquid weight ratio in feed;
- size and shape of the particulate solids;
- specific gravity differences between solids and liquid;
- presence of flocculant;
- viscosity;
- temperature of the feed stream;
- method of flocculant application;
- particle wetting characteristics;

Figure 2. Indicative ranges of paste properties after P. Williams (Jewell 2002)
• feed method/arrangement;
• rake time and speed;
• wind and evaporation.

The most frequently used reagents in the thickening process are (Bedell et al. 2002):

- **flocculants**: high-molecular-weight synthetic or natural polymers that aid in enhancing the settling rates of most suspended solids. They are generally polyacrylamide-based compounds manufactured in anionic, non-ionic and cationic forms;
- **coagulants**: natural minerals such as alum, lime, ferric salts, etc., which are effective for colloid suspensions. They are less effective than flocculants.

Flocculant selection aspects (Bedell et al. 2002):

- design of the actual dewatering equipment to be used;
- minerals present in the slurry: surface chemistry, concentration, particle size;
- chemical make-up of the slurry liquid: ionic strength, pH;
- type of floc structure required: weak, strong or small.

Common components of thickeners (Bedell et al. 2002):

- tank;
- feedwell;
- overflow and underflow withdrawal system;
- rake;
- drive;
- support structure.

Cyclones cannot generally be used solely as the first stage of dewatering because slimes are lost in the overflow. However, cyclone overflow can be dewatered in a conventional thickener and remixed with dewatered cyclone underflow or an alluvial material to form a paste. For a common milling operation with quartz, carbonates and feldspars as predominant minerals, the underflow from the thickener should be 65 to 70% by weight.

The underflow from a conventional thickener should be a stable slurry. A stable slurry does not exhibit segregation of particle sizes or rapid settling of large particles. A stable slurry can be easily pumped with centrifugal pumps, and pipeline velocity is not so critical as with dilute slurries. Many different types of dewatering filters can be used, including disc and drum vacuum filters, horizontal belt vacuum filters, belt filter presses and hyperbaric disc filters. The product of the final dewatering step is a moist filter cake that can be handled by belt conveyors. Some storage of filter cake is usually necessary to level out surges in the paste preparation process. The filtration step can be avoided in the preparation of paste by mixing the thickener underflow slurry directly with a suitable dry alluvial material to produce a paste mixture.

Using high-density thickeners to produce a high-slump paste directly from a dilute tailings slurry to prepare pastes is becoming the preferred method. High-density thickeners have a deeper sludge bed than conventional thickeners and the rake is submerged in the sludge bed. Consequently, rake torque requirements are high. The aluminium industry has pioneered special high-density thickeners for processing red mud, so that it can be deposited in a stack or mound. The Baker Process Deep Cone Paste Thickener System is designed specifically to produce pastes with relatively high viscosity and a yield stress. The thickener maintains a deep blanket of settled solids, maximizing gravity compression, and achieving discharge solids that can approach the limits of flowability. The solids content of the pastes will be greater than for any traditional thickener operation. The target is to control the rheological properties short of consolidation where fluid flow stops. The control techniques are encompassed in the geometry of the rake and underflow removal methods. The geometry of the thickener tank is designed to handle high viscosities and yield stresses. Effective flocculation is important, and this is accomplished using a specially designed feed dilution and flocculant mixing system as part of the feedwell (Slottee and Schreiber 1999).

The components of a paste mixture, including filter cake, cement, aggregate, and water, must be mixed thoroughly to produce a homogeneous paste for pipeline transportation. A paste mixing plant is similar to a concrete batch plant. Components must be accurately weighed and rapidly supplied to the mixing process. A batch mixing process is easier to control and is usually
preferable to a continuous mixing process. High-intensity mixers developed by the concrete industry are suitable for mixing tailings paste. The historic development of thickeners is schematically illustrated in Figure 3 (Bedell et al. 2002; Slottee 2003). The high-rate thickeners were developed by the two pioneers – the EIMCO Process Equipment Company (Baker Process) and Enviroclear, in the 1980s. Understanding the ‘flux and concentration’ relationship for flocculants resulted in a special deep feedwell and special dilution features in thickener design. Key to the process is the compressive yield stress and permeability of the thickened material (Scales and Usher 2003).

The routine dewatering for most tailings is a combination of thickening followed by vacuum filtration. Thickening efficiencies have improved over recent decades as a variety of flocculants and reliable dry flocculant mixing and addition systems became available. Thickener capacities have improved from the routine historical rate of 0.45 t/m²/h to some conditions that allow 2.7 t/m²/h to be used.

The ultra-high-rate and ultra-high-density thickeners (Figure 4) evolved in the 1990s. They encompass a deep thickener tank (Green 1995) and use specially designed dewatering centre cones. This feature, plus the cylinders ringing the outside of the feedwell, produces a good clear overflow. The rapid removal of water from the feed collapses the hindered settling zone of the thickener taking solids from the free settling zone into the compaction zone. The deep tank plus the 60° cone provide a deep compression zone that results in high-density underflow solids (Figure 8). In an example of its application, two 12 m diameter E-CAT™ clarifier thickeners replaced two 100 m diameter conventional thickeners while producing a consistent underflow of >60% solids and overflow clarity of less than 50 ppm. These thickeners require a high degree of instrumentation and automatic control, plus variable speed controlled pumps (Bedell et al. 2002).

A large variety of flocculants are now available. Most suppliers optimize their reagents as to ionic specificity and the molecular weight of the polymer. Reagent screening is followed by graduate cylinder testing of the preferred polymer to allow settling rates to be determined at several addition levels, as well as determine the terminal density of the particular tailings. Once the polymer has been mixed with the slurry feed stream at the right density in the feedwell, gravity has to do the rest. Sometimes, extreme dilution may be necessary before effective flocculation and settling occurs. Ultra-high-density ‘paste’ thickeners produce underflows of paste consistency by (Figures 5 and 9):

- maximizing flocculant flux efficiency;
- using feed dilution systems (E-Duc® System or AUTODIL®);
- using a deep tank for compression;
- using a 30–45° cone;
- using a specially designed raking system;
- using shear thinning principles;
- using a high degree of instrumentation.

Figure 3. Thickener evolution (Bedell et al. 2002)
TESTING

Numerous tests are needed to determine suitability for paste transport (Brackebusch 1994; Zou 1997; Ouellet et al. 1998; Fourie et al. 2002):

<table>
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<tr>
<th>Pilot plant tests</th>
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<tr>
<td>Thickening at plant site</td>
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<tr>
<td>Liquid and paste limits</td>
<td>Shear strength</td>
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<tr>
<td>Porosity</td>
<td>Process water quality</td>
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<tr>
<td>Permeability</td>
<td>Viscosity</td>
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<td>Abrasiveness</td>
<td>Liquefaction</td>
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<tr>
<td>Bin flowability</td>
<td>Consolidation and desiccation</td>
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<td>Slump vs. water content</td>
<td>Water retention curve</td>
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<tr>
<td>Thickening test</td>
<td>Hydraulic conductivity</td>
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<td>Filtration test</td>
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The rheology of a paste is controlled by a number of different variables such as particle-size distribution, particle surface chemistry, liquid viscosity, flocculant quantity and characteristics, concentration of particles and the amount of energy put into the mixture. A common means to measure the rheological properties of a paste is the ASTM slump cone test, which uses a truncated cone 305 mm (12 inches) in height. The cone is filled with paste and then removed, allowing the contents to assume a pile shape with a natural slope. The distance of the top of the pile from 305 mm is the slump. A slump measurement reflects the yield stress of a paste. Dense paste would have a low slump of 50–200 mm (2–8 inches). Materials at the transition between a slurry and paste would have high slump, up to a maximum of 305 mm (12 inches). The slump value determines the suitability of the paste for disposal – for most applications a slump of 175–250 mm is ideal (Slottee and Schreiber 1999; Fourie et al. 2002; Newman 2003).

The design procedure for a paste plant summed up by Tenbergen (2000) is:

- laboratory rheological testing of tailings to review
the suitability of the tailings as a paste for underground or surface disposal;
• uniaxial cylinder strength testing to define the paste recipe;
• pump loop testing to assess paste pipeline friction losses for design purposes;
• paste plant flowsheet development. At this point major design criteria will be assessed and agreed upon, such as:
  – the tailings dewatering method;
  – requirements for binder and aggregate addition;
  – requirements for pumping for surface or underground disposal;
  – batch mixing or continuous mixing of the paste recipe components.

Figure 6 shows typical solids by weight versus slump relationships for relatively coarse gold tailings, base-metal tailings and blended gold tailings with aggregate (Tenbergen 2000).

FLUID MECHANICS OF PASTE MIXTURES

Paste mixtures are non-Newtonian fluids, usually with Bingham properties (Boger 2003). Many pastes exhibit pseudoplastic features, which means that viscosity decreases with greater pumping rates – a beneficial property for pipeline transportation (Brackebusch 1994). Yield stress, being one of the key transport parameters for pastes, is shown as a function of concentration for various tailings in Figure 7 (Boger et al. 2002)

Horizontal paste transportation distances may be in excess of 1 km. Pipeline diameters range from 100 to 200 mm and flow velocity is less than 1 m/s, while typical dilute slurry velocities are around 3 m/s. This reduces friction losses and energy consumption by
nearly one order of magnitude due to a proportionality to the square of velocity. Figures 8 and 9 show the underflow of ultra-high-density thickened tailings and paste consistencies.

In the design of a paste plant and delivery system it is necessary to assess pipeline friction losses for different slump pastes. Friction losses will decrease as the slump of the paste increases. Friction losses, however, can vary widely between pastes from different mines even though the slumps may be similar. Figure 10

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**Figure 6.** Solids content vs. paste slump (Tenbergen 2000)

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**Figure 7.** Yield stress as a function of concentration for various tailings (Boger et al. 2002)
shows friction losses for a particular gold tailings paste, at various paste slumps, with and without aggregate addition. Friction losses varied by a factor of five in pump loop tests between pastes varying in slump between 178 and 254 mm. Surface disposal of paste would be possible with a slump of 254 mm (Tenbergen 2000; Pullum 2003). The high friction loss experienced with the low-slump paste limits the horizontal distance to which paste will flow under gravitational forces, even though a lower slump is desirable from the paste strength point of view. The addition of aggregate to the gold tailings lowers the friction losses significantly and allows a wider distribution. As a basic design step, friction loss data from pump loop tests are used (Tenbergen 2000).

Both centrifugal and positive displacement pumps can be considered for slurry and paste transport. Slurry-handling centrifugal pumps are compact, relatively cheap, robust and versatile machines and are almost universally used in low-head slurry transport systems. Lining and special alloys increase wear resistance. To obtain the heads required for long-distance pipelines, centrifugal pumps are connected in series. To increase capacity, centrifugal pumps are arranged in a parallel configuration (Paterson et al. 2002; Paterson 2003). Positive displacement pumps provide high discharge pressures, and capacities range from 30 m³/h to 800 m³/h at pressures of up to 30 MPa. The disadvantage is the high capital cost, which is often offset by their low operating cost and high reliability.

**ADVANTAGES OF PASTE TECHNOLOGY**

The main advantages of paste technology are:

- reduced capital cost (no large dam is required);
- increased safety;
- water conservation;
- decreased volume of disposed tailings;
- reduced soil and groundwater pollution;
- inhibition of acid mine drainage (AMD);
- reduced liability for the mine;
- possible co-disposal of other mine waste;
- improved conditions for reclamation;
- no segregation of particles;
- easy rain-water drainage due to sloping tailings surface;
- potential use as a foundation material (Crowder et al. 2000; Debreczeni and Debreczeni 2001).

A major factor contributing to increased safety is that even if the (small) dam required by PT failed, the material behind the dam, being well-consolidated and without water can slump but cannot flow. The conventional slimes pond has been eliminated and, without water to wash out the tailings, a dam collapse is a local
DISADVANTAGES OF PASTE TECHNOLOGY

- Paste production may involve additional costs due to the need for a paste plant;
- paste technology is more complicated than conventional methods, and requires a high level of technological infrastructure;
- if there is a need for storage of process water, this requires special arrangements.

ECONOMICS

Dams are notoriously expensive structures. Surface paste technology significantly reduces the cost of embankment construction, engineering, monitoring, closure and reclamation. However, the high technology of the paste plant is reflected in its price of US$3–10M (for a daily paste production of 3000 to 10 000 tpd). Newman (2003) reaches the conclusion in his cost analysis for a ten-year, one million tonnes per year mining operation in the Barrick Gold mine in Bulyanhulu, Tanzania, that paste technology leads to lower overall mine-life costs (US$15.3m) compared to conventional tailings technology costs (US$16.2m). The operating
costs are greater than for the tailings pond system – reflecting the added processing cost of paste manufacture; the capital costs are similar; and reclamation costs are significantly lower.

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