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Perceived and realized benefits of paste and thickened tailings for surface deposition

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SYNOPSIS

Interest in the potential use of high-density, thickened tailings has recently increased significantly. Rea
new technology vary across projects, but commonly include the need to conserve water, perceived lov
failure, potential easier closure, or even reduced overall costs. As with any new technology, there has b
overstate its potential benefits. This paper reflects on whether or not the potential benefits that have b
and thickened tailings have been realized. Using a grading system, thirteen benefits that were ascribed
some years ago are evaluated. Data is taken from case studies, and it is suggested that the key proven
reduced operating costs in some cases, reduced wall-building costs, and reductions in water consump
benefit that has not been universally achieved is a reduction in the footprint of the tailings facility. Rep

highlight the sometimes confusing nature of trade-off studies. Unless full life-of-mine costs are consic
be misleading and incorrect. The need to establish a consistent basis for comparative studies is discus

Keywords: high-density, tailings, benefits, costs, water consumption.

Introduction

With current (July 2011) high prices for most mineral resources, lower grade deposits are increasingly not uncommon for a grade of less than 1 g/t to be considered viable in some gold mining operations. increasing demand for minerals, this results in the requirement to safely store and manage larger and particular concern are the volumes of tailings produced, as failures of tailings storage facilities (TSFs) common, and much more damaging, than failures of waste rock dumps.

It is with this in mind that the mining industry internationally has been investigating alternative optio mine tailings. Conventional practice requires pumping large volumes of water together with the mine water must subsequently be managed. It is this free water that has led directly to the vast majority of f as well as contributing to problems such as groundwater contamination and the destruction of vegeta environment due to contaminant migration in the vadose zone. One potential alternative solution is t density thickened tailings (TT), which is often (usually erroneously) termed paste tailings.

An alternative: paste and thickened tailings

The annual seminar on the topic of paste and thickened tailings usually draws in excess of 300 delega continuing interest in this topic; this paper provides a perspective of whether the technology (referred has lived up to the envisaged benefits. In 2002, the first edition of a book, 'Paste & Thickened Tailings 2002) was produced by the Australian Centre for Geomechanics, followed in 2006 (Jewell and Fourie) edition. In this book, Tacey and Ruse (2006) discussed the key drivers for adopting P&TT. Their summ benefits is reproduced as Table I. An additional column has been added to this table; it is a grading, o whether the stated benefits of P&TT have been realized over the past decade. The idea of the grading i the ASCE to evaluate the state of the USA's infrastructure. However, this latter grading system is based capacity, condition, funding, and resilience, and is not appropriate for the present purposes. The gradi intended to be specific to the evaluation of P&TT, and is:

- A - has achieved benefits, with perhaps some minor exceptions, clearly superior
- B - has largely achieved benefits but some concerns remain
- C - no substantial benefits (or impairment) compared with conventional approach evident
- D - has largely not achieved benefits, although some advantages are evident
- E - has not achieved benefits; clearly inferior. These evaluations are subjective and some pr take umbrage at some of the ratings. Nevertheless, they provide a point of departure for evalua the promise of P&TT is being realized. Much of the data used to arrive at these ratings is contai proceedings of the annual seminars.

Basis for comparison

Terminology regarding high-density tailings (encapsulating both paste and thickened tailings) is a co and it is not possible to provide a simple, all-encompassing definition. The word 'paste' is convenien however, when applied to surface disposal, it is misleading as there are probably only two or three fa

that deposit a true paste. The vast majority of new-generation, high-density tailings thickeners can pro
tailings. Figure 1, reproduced here from the second edition of the 'Paste Guide' (Jewell and Fourie, 20
terminology in common use. The horizontal axis is a measure of consistency or density, usually define
content', usually on a mass basis. The vertical axis is a measure of strength, usually defined as the she
increasingly measured using a rheometer fitted with a shear vane able to measure strengths of tens of

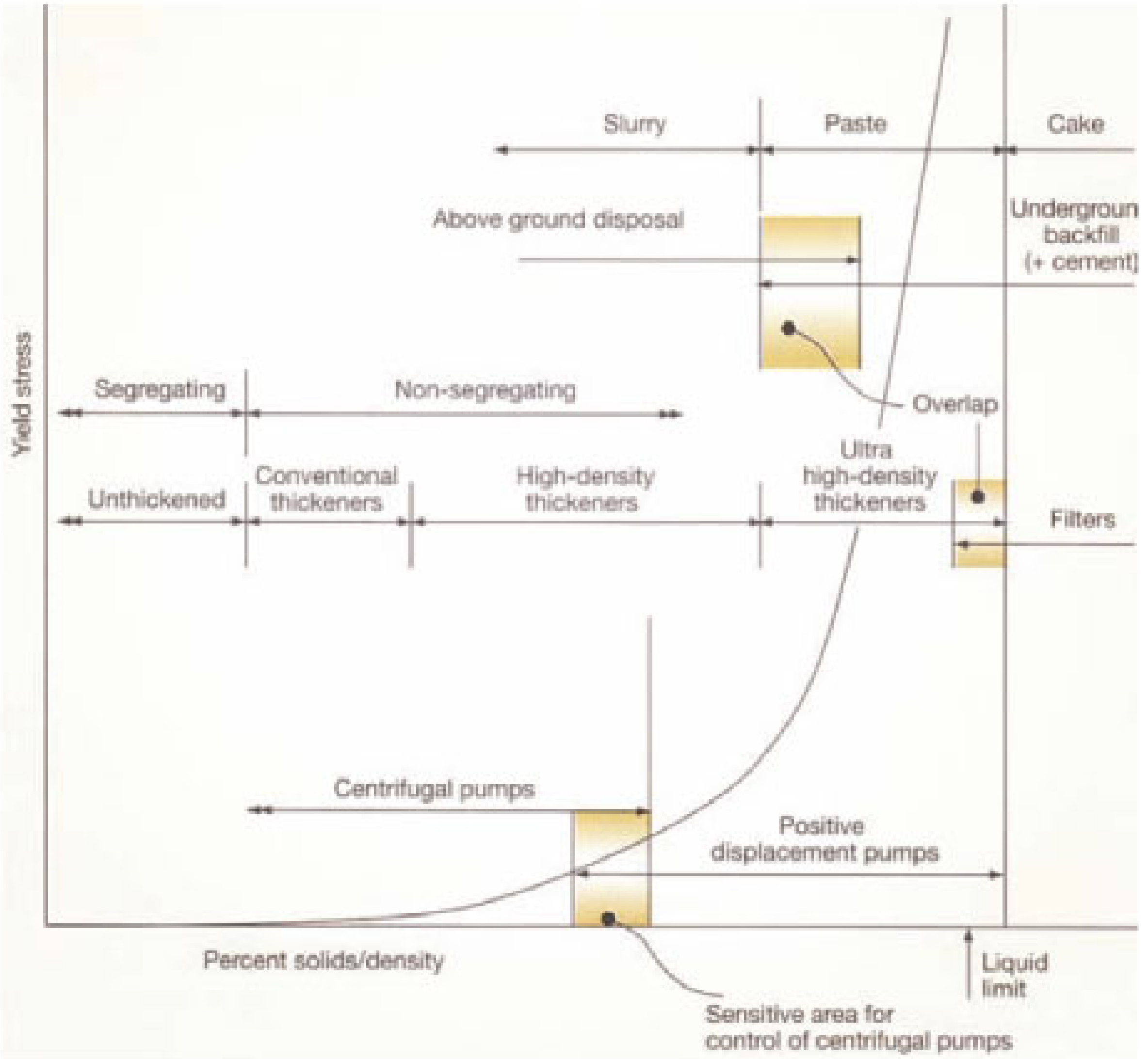

Figure 1—Illustration of terminology used in description of 'Paste and Thickened Tailing
after Jewell and Fourie (2006)

Conventional thickeners produce material that has virtually zero yield stress and, when deposited in a
percentages of the transported water, resulting in elevated ponds of decant water. A definition of 'past
a cut-off value of yield stress, with values of 100 Pa and of 200 Pa both having their advocates (note tha
drawn between the yield stress of thickener underflow tailings and that of the material deposited at th
significantly as a result of shear stresses applied during transport). As can be seen in Figure 1, the cons
to approach the liquid limit of a material, and transport of the material may require the use of positive
the capital cost of which is extremely high.

The vast majority of operations discussed in this paper therefore fall into the 'high-density slurry' regi
transport is still possible using centrifugal pumps. However, conventional thickeners are no longer ad
versions of deeper thickeners, including high-density, high-rate, deep-cone, paste, etc.

A reasonable question might be 'what is the real difference between conventional and high-density th
to as TT from now on)? Key differences are that TT releases very little, if any, bleed water, there is virtu

segregation down the beach, and the material exhibits a finite, measureable yield stress. One of the ke
TT is the promise of reducing the volume of water used per ton of tailings deposited. Figure 2 illustrat

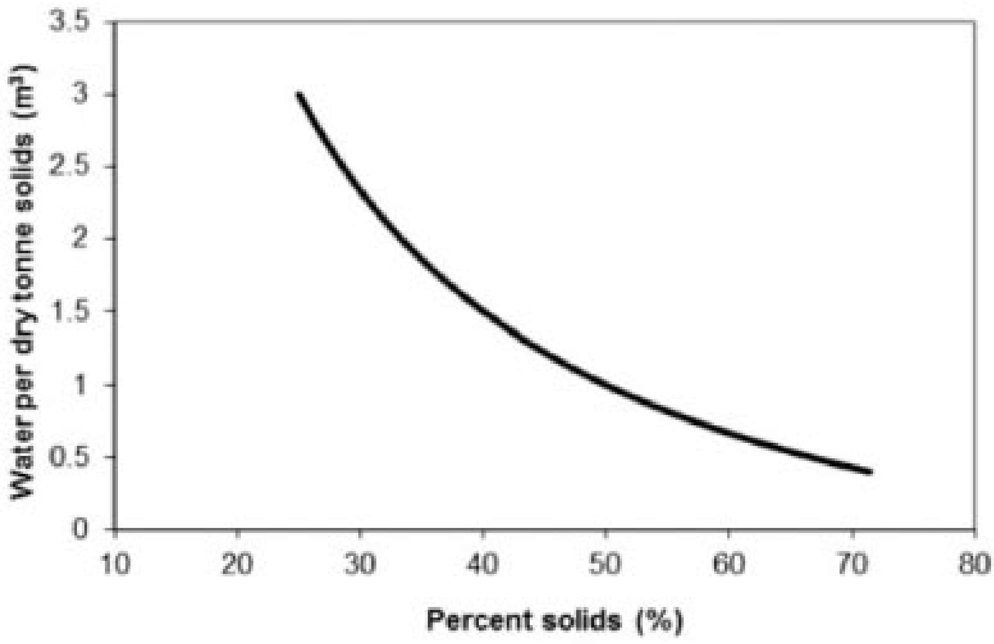

Figure 2—Variation of transported water volume with tailings percentage solids (for specific gravity = 2.7)

The variation shown in Figure 2 is not necessarily the true reduction in water used per dry ton of tailin
volume of water transported per dry ton. As an example, by increasing the solids content from 32% (a
conventional tailings) to 60% (noting that values in excess of 70% have been achieved, (McPhail *et al.*,
per dry ton is transported to the TSF. This additional water is recovered during the thickening process
available for re-use. Upon deposition at the TSF, very little bleed water is usually released, unlike con
some of the additional water transported to the TSF is potentially recoverable from the TSF. There is n
these potential water savings are real or not; indeed, Lyell *et al.* (2008) argued that, as long as the TSF i
of rise, it acts like a very large gravity thickener and just as much water can be recovered as is possible
However, data emerging from field implementation of TT, as discussed later, contradicts this view and
are very real.

Have the promises of P&TT been realized?

Williams *et al.* (2008) provided a review of over 30 operations around the world using TT, and since th
operations have come on stream. There is thus a reasonable amount of information now available fro
draw comparisons between TT and conventional systems. The topics are dealt with chronologically, a
very superficially, due to the limited amount of relevant information available in the literature.

Similar capital and reduced operating cost to wet disposal

We immediately encounter a snag when attempting to evaluate this criterion. Published cost comparis
the same battery limits. For example, van der Walt *et al.* (2009) provide (predicted) cost comparisons b
approach and three different TT systems. They concluded that the conventional approach was cheape
systems in terms of both capital expenditure (capex) and operating expenditure (opex). However, thei
only components up to, but excluding, the TSF, which is inappropriate. Significant construction saving
operations) are possible with TT operations, as discussed later.

Alcoa introduced a form of TT, called 'dry stacking', in 1985 which, according to Cooling (2002), cost m
implement. Alcoa deposits around 39 kt/d of bauxite residue at three facilities in Western Australia. Pa
cost was estimated at 7-8 years. The company found operating costs to be about 70% of the previous '
report a number of proven benefits, as discussed later. At Sunrise Dam, a gold mining operation in We
hypersaline groundwater is used for processing, comparative costs at the time of design were A$0.24 p
per ton for conventional tailings. Actual costs for the TT operation have been around A$0.3 per ton, wi
largely from increased regulatory requirements regarding closure.

Williams and Seddon (2004) present data for the Century open-pit lead/zinc mine in Australia, a 10 kt/
calculated net present value (NPV) of the chosen TT operation was A$43.3 million, as opposed to A$65
conventional operation. This operation, which is located in a sub-tropical climate, uses single-point d
valley, with tailings thickened to 40% solids. There are many published results of cost comparisons ca
feasibility studies. Reference to these has been avoided here, except for two considered worth mentio
of the operations. For the Quebrada Honda facility in Peru (Serpa and Walqui, 2008), which will be a 1
was estimated to be 19% less with a TT operation, with the final decision also being influenced by the
savings over the 35 year life of the facility. Rayo *et al.* (2009) conducted a trade-off study for an expansi
facility in Chile, a 230 kt/d operation, where the costs of a TT operation on the existing TSF were comp
a new, conventional facility some 50 km away. They showed no distinct difference in NPV; however, th
estimated to result in water savings of up to 65%.

Although the data is limited, it seems that opex may be less for a TT facility than for a conventional on
flocculant costs may become important. For capex, the benefits are even less clear, especially if a decis
positive-displacement pumps, the capital costs of which are high, although these costs may be offset b
power costs, reduced auxiliary equipment requirements, better pump efficiencies, and lower maintena
Finally, it must be noted that there were no studies found that directly compare the closure costs of th
to be seen whether the perceived benefits of TT materialize. A TT facility has the advantage of produci
prone to erosion and thus requires less investment in the cover system, but can suffer from the disadv
landform with a larger surface area than a conventional facility, thus potentially requiring a greater vo
Given the lack of data and the conflicting experiences mentioned in the literature, a neutral grading of

Costs accrued during operations

This topic has been covered in the previous section, and the evidence certainly points to reduced ope
result of simplicity of operation and the reduced volumes of wall-building material (see later). This c
be an advantage of TT systems, although some operators report day-to-day management requiremen
being greater than originally envisaged (Paterson, 2011). A positive grading of B is proposed, in recog
that, although operational costs remain an issue, they are likely to be less than for an equivalent conv

Increased deposit strength

This topic has been assigned a C grading; not because TT has failed to deliver the stated promise, but
soon to make a judgement. No TT facilities have been subjected to a major earthquake (to the author'
magnitude earthquake in 2010 in Chile did not result in the failure of any (conventional) TSFs built us
method of construction. Only once a TT facility has exhibited similar successful behaviour, will it be p
conviction that increased strengths are likely. Nevertheless, the experience to date suggests this is like
that increased stacking heights were being achieved by Alcoa because of the greater strength of the de
found that switching from a conventional approach to a TT deposit at the Musslewhite Mine in Canad
increase in density. These authors did report slow drying, with associated slow rates of strength gain,
nevertheless have produced higher strengths than conventional tailings. McPhail *et al.* (2004) report a
density, but figures were not given. Apparently, there was an increase from an average of 1.8 t /m^3 for
an average of 1.95 t/m3 for TT (Anon., pers. comm., 15 December 2011).

Decreased land footprint by at least doubling practical stacking height

Presumably the reason that Tacey and Ruse (2006) consider that a TT operation will result in a decrea

expected (and largely proven) increased beach angle that results with TT. However, cognisance also h
method of deposition used. When a central thickened discharge (CTD) operation is chosen, tailings fl
deposition point(s), following the path of least resistance. In the absence of a perimeter retaining emb
results in a very large footprint, given that overall beach slopes achieved to date have rarely exceeded
layout improves the land utilization, but generally requires a site that is long and relatively narrow (A
December 2011). Land footprint has thus been assigned a D grading, despite the numerous successes
discussion. It is suggested that future case studies will illustrate improved land utilization, and this ra
accordingly.

Jewell (2004) discussed the Peak gold mine in Australia, which has operated since 1992 and now uses
tailings thickened to 60% solids are deposited into a shallow gulley adjacent to the plant, thus minimi
perimeter embankments and maximizing the tailings volume stored on the available footprint. As the
increased, saddle dams have been constructed as necessary, with the beach slope achieving an averag
maximum of 2%. Cooling (2007) confirms that dry stacking using TT has achieved higher densities an
Alcoa deposit the bauxite residue at around 50% solids (after removing the sand fraction, which is use
construction) and utilize mud-farming techniques to increase the solids content to 70% prior to future
mentioned, the embankments are constructed, at a slope of 1:6, using the recovered sand fraction. Wi
these embankments, the reduced footprint would not have been achievable. Given the proximity of re
in the area and the resulting price of open land (which would have to be acquired in order to accomm
of a conventional facility), the thickened tailings option proved a less expensive option.

Oxenford and Lord (2006) describe two operations that increased the utilization of an existing footpri
operations and depositing on an existing TSF ('piggybacking'). The Myra Falls facility had operated si
conventional tailings deposition and switched to a TT operation by installing a 25 m diameter thicken
around 67% solids. Use of the existing TSF footprint was successfully achieved. A second example is th
TSF. Production began in 1981 and ceased in 2003. In 1995, a 26 m diameter, 3.5 m deep thickener was
producing tailings at 52% solids, which was pumped 1.7 km to the existing TSF using piston pumps. T
a beach slope of around 3%. Another piggybacking example is the Musslewhite operation (Kam, 2011)
existing footprint by thickening to 70% solids, and consistently achieved the design beach slope of 2%
head of the beach). A final example of using an existing footprint is discussed by Cooper and Smith (2
treatment plant (CTP) facility in South Africa, where diamond tailings (containing a high content of sm
to 60% solids, using five 15 m diameter deep-cone thickeners, and is pumped over 5 km to the TSF us
pumps. The required beach angle has not been achieved, requiring the raising of the perimeter emba
schedule. The beach slope is reportedly around 1%, but is gradually increasing as operational change

Li *et al.* (2011) discussed an example of a TT facility in a tropical climate, the Gove bauxite residue sto
Australia. A system was introduced in 2006, producing a residue at 45-51% solids that can be 'dry-stac
'mud-farming' techniques to further increase density, reporting a 20% reduction in volume as having

Decreased demand for borrow materials for construction

In Australia, wall raising costs (required by conventional upstream construction) for a typical medium
A$ 1-2 million per lift (McPhail *et al.,* 2004). The benefits provided by TT operations in this regard are
of A is considered warranted. Reported savings in wall building costs have been reported by Jewell (2
mine, by McPhail *et al.* (2004), and McPhail and Brent (2007), who noted a saving of A$2.5 million at th
Williams *et al.* (2006) for the proposed Miduk Copper Mine in Iran, and Cooling (2007) for Alcoa's ope
Australia. There are no reported cases of increased requirements for borrow material.

Reduced risk of leachate seepage

A grading of A may have been appropriate, but a B was decided on because once again it may be too s
judgement. Nevertheless, the omission of an elevated decant pond using TT should intuitively result
Furthermore, the volume of water expelled during self-weight consolidation is also likely to be reduc
available that confirms this intuition. Cooling (2002) described how the switch to a TT system was stro
need to reduce seepage to groundwater, a goal believed to have been attained (Cooling, 2007) as no c

has been measured in boreholes around the site perimeter since introduction of dry stacking and the i underdrainage. McPhail *et al.* (2004) reported the results of piezocone tests at Osborne that showed no pressures to the depth tested (7 m) and concluded that seepage rates had reduced by between five- an (2008) describe two field studies (at the Peak and the Elura operations in Australia) where sampling th the TT tailings facilities showed *in situ* degrees of saturation between 60-80%, with the occasional spik the surface. Clearly, the lack of excess pore water pressures and degrees of saturation well below 100% seepage is likely.

Reduction or elimination of ponding and low-strength mud deposits

As already noted, a TT operation invariably eliminates the decant pond, confirmed by Jewell (2004) an others. One exception is the Hillendale facility in South Africa, where mineral sands fines are thickened using positive displacement pumps to a TSF where deposition occurs from a ring-dyke, producing a fa conventional TSF, although at higher densities.

The piezocone strengths reported by McPhail *et al.* (2004), the low degrees of saturation at Peak and El 2008), and the increased solids contents (and thus strengths) reported by Cooling (2007) and Li *et al.* (2 discussed. They all tend to confirm the same thing; a higher strength deposit. However, a word of caut absence of a competent perimeter embankment means that if a low-strength deposit (or layer) develo retain the material, unlike most conventional TSFs, where the finer and weaker material is (usually) co the TSF. Despite these concerns, a B grading was assigned.

Prompt creation of firm, convex draining surface at completion

A grading of C is considered appropriate, once again primarily because it is too soon to make a subjec few examples of TT facilities having been closed, so assigning a grading to this topic requires speculat certainly points to the likelihood of a firmer, more accessible surface resulting from a TT operation. Sh describe the Bulyanhulu operation in Tanzania - a gold mining operation commissioned in 2001. It is that true paste material, which is prepared for underground backfilling using filters, is subsequently di surface deposition. The tailings are usually transported at around 78% solids, using positive-displacem distance of 2 km to the TSF. Deposition is rotated between five 12 m high towers, and unlimited access week of deposition. Other examples that support a positive grading include Cooling (2007) and Willia

Earlier, better surface leaching and drainage

A grading of D has been assigned, not because the stated advantage has been proven to be false, but b convincing evidence that it is true. This criterion envisaged early leaching of toxicants from surface and establishment of vegetation, coupled with reduced duration of dust generation. Apparently, studies at no difference in the rates of acid generation after switching from a conventional to a TT system. (Anon December 2011). There is no published evidence of accelerated leaching of contaminants, and the dus either. Indeed, anecdotal reports suggest that dust can be a significant problem with some TT deposits can dry out between deposition cycles, producing conditions conducive to dust generation. This issue watched carefully.

Potentially large reductions in water use

This topic possibly has more convincing evidence in its favour than any other, and it was therefor assi water continues to rise in some areas and availability decreases in others, it is among the most import the choice of one technology over another (cost of course being the other). The discussion is divided i where the need to reduce water consumption has driven the decision to go with TT, then operations w quantified.

Luppnow and Moreno (2008) describe the decision to adopt a TT system for the 95 kt/d Esperanza fac save 80 m m^3 of water per year. As mentioned previously, the 147 kt/d TT operation at Quebrada Hon expansion (Rayo *et al.*, 2009) were driven by water concerns. Busani *et al.* (2006) describe the dire need Botswana, with the choice of TT being driven by the need to reduce water use by as much as 50%. In Ir copper tailings using twelve 24 m diameter deep-cone thickeners was driven by the need to maximize (McNamara *et al.,* 2011). The 96 kt/d of tailings will be discharged by gravity directly to the disposal ar located near the head of a valley (with an engineered embankment at the low point). The Voorspoed c chose TT, using two 18 m diameter high-rate thickeners to provide the required water savings (Coope Wu *et al.* (2011) report that the Wushan copper mine in China decided to thicken their 40 kt/d tailings, thickeners, to 70-72% solids in order to reduce water consumption. Wushan operates in extremely col annual temperature of -0.7°C). Wu *et al.* report a water saving, but do not quantify it.

Quantifications of water savings have been provided by Wallace (2004) as 6% for the Murrin-Murrin o unusual application, as it involves only moderate thickening, from 36-39% solids, to improve autocla McPhail and Brent as 40% for the Osborne Mine (2007). Without quantifying the reductions, Cooling (Lord (2006) referring to the Ekati diamond operation in South Africa confirm reductions in water usa

Reduced potential for liquefaction

This potential benefit remains speculative, and has therefore been assigned a D grading. Although inc have been achieved, as discussed earlier, the true test of the liquefaction resistance of TT will be the e to a major earthquake. Further caution is also warranted. The production of TT requires the addition o flocculants. There is no research available on the nature of the structure of the tailings that is produce particularly the structure that remains when the flocculants inevitably degrade. We need to be certain facilities that may be inherently unstable in decades to come.

Potentially reduced heating, lower water demand

Despite some evidence that heating requirements are reduced, it is not entirely convincing and a neut consequently been suggested (the issue of lower water demand has been dealt with previously). The J processes bauxite from up to six different sites around the world, and since 1987 has used the TT tech deposit residue at 68% solids (Oxenford and Lord, 2006). They report significant heat recovery from th expected that adoption of TT operations in the oil sands industry will similarly enable significant heat

Reduced reagent requirements

A grading of C is assigned, despite a number of reported cases where tangible benefits accrued throug Oxenford and Lord (2006) found significant recovery of sodium hydroxide from the thickener at the Jo Li *et al.* (2011). Outside the alumina industry, this issue does not seem to be a key driver at present, alt simply because it has not been quantified as yet. The potential for increased flocculant consumption i was not assigned a B grading.

Other key issues

Although not listed in Table I, it has become clear that one of the key factors to be quantified when eva TT scheme, be it a greenfield site or a retrofit operation, is the beach angle that will develop. Unlike co where the beach slope angle does not dictate the footprint of the deposit (although it does govern the water management requirements), a TT deposit footprint can be highly dependent on the beach slope confining embankment is planned. Despite claims that beach slopes of as much as 10% are achievabl indicates this is not so. It is also difficult to achieve a consistent beach slope. Williams and Seddon (20 erratic thickener behaviour resulted in a beach with slopes of only 0.3-0.4% initially, but after refinem procedures, a value of 1% at the head, to 0.5% at the toe, was achieved. Williams *et al.* (2006) describe which was commissioned in 2005 to treat 15 kt/d. The decision to choose a highly thickened tailings w beach slope of 4%; however, the actual slope was reported as being about 2.4%, with differences attrib expected solids content and more fines in the feed. This is a key issue that could potentially delay the Current approaches to predicting likely beach slopes are empirical and, at best, subjective. It is sugges techniques such as computational fluid dynamics or smoothed particle hydrodynamics are likely to b

Another aspect that was discussed in the original version of the 'Paste Guide' (Jewell *et al.*, 2002) but is the potential for TT to reduce the generation of acid drainage; the argument being that the non-segreg in tailings with a greater water retention capacity, which does not de-saturate as readily as convention This argument was presented as justification for a proposed paste tailings facility at the Neves-Corvo Portugal. Despite convincing results obtained from field trials using small test facilities, discussed by Verburg (2010), it appears that the owners considered it too high a risk and opted for a conventional fa disposal (Real and Franco, 2006).

As a final note, the ability to 'scale-up' appropriate deposition experience from one site to another, lar proven for TT operations to date, whereas it is fairly routine for conventional tailings operations.

Conclusion

The gradings in Table I for various potential advantages of a high-density tailings operation indicate t technology provides many benefits and is likely to be superior to a conventional tailings deposition a situations. However, this is not necessarily the case. Firstly, the references that were used in compiling largely from the annual seminar series that discusses 'Paste and Thickened Tailings', as these seminar and case studies that are current. It is possible that presenters at these seminars (particularly vendors) present successful case histories than failures, thus perhaps providing a biased view. Further, there is published information on projects where a TT operation was rejected in favour of a conventional ope

Although it was not included in the original table of perceived advantages, another aspect that is some TT technology is reduced closure costs. The rationale for this is not entirely clear, particularly given th result from a deposition strategy such as CTD. Documented evidence of reduced closure costs is a cru particularly as the issue of sustainable mine closure becomes increasingly crucial to ensuring ongoin mining activities.

Finally, although TT technology has certainly proved favourable in many circumstances, and holds th reduce water wastage in the mining industry, as well as providing more stable and enduring structure case, we need to guard against hubris, and not necessarily believe all the promotional material produ There are also new technologies on the horizon, such as in-line thickening and high-volume filtration time, supplant current TT technology. What is clear is that the recent acceptance of TT as a viable alter tailings deposition has increased awareness of this critical aspect of mining (tailings management), ar thing.

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