KEYNOTE ADDRESS

TAILINGS WASTE MINIMISATION, RHEOLOGY, AND THE TRIPLE BOTTOM LINE

B. Hart
Department of Chemical and Biomolecular Engineering,
The University of Melbourne, Victoria, Australia
D.V. Boger
Laureate Professor, The University of Melbourne, Victoria, Australia

ABSTRACT

The minerals industry is very upbeat about sustainable development. Many companies have sustainability managers. Unfortunately most of their effort in sustainable practice is directed towards the social and stakeholder interaction in the community. Very little effort is being made to apply sustainability practices to management of liquid waste tailings. Even though technology exists now to move from wet to dry disposal technologies, the industry still insists on building traditional dams that defer the costs associated with dealing with waste until some time in the future when the company is often able to escape the liability.

The paper is a plea to those who have to deal with waste management issues on a day-to-day basis to communicate with those in the corporate structure who are responsible for sustainability issues. New projects worldwide will have a greater difficulty in being approved if the industry does not, to a large extent, improve its performance in regard to the management of particulate fluid wastes. The paper presents some positive and negative examples of sustainable behaviour associated with tailings and concludes by summarising the rheological technology which is available today to deal with suspensions at a high concentration, which in fact is where the industry must move if it is going to recover more water and effect more sustainable practices.

1. INTRODUCTION

Sustainability and the Triple Bottom Line are being promoted throughout the mining industry, largely through promoting social sustainability initiatives such as stakeholder involvement and community development programs. There are many definitions of sustainable development. For example, one is that sustainable development is about strengthening the business while reducing negative social and ecological consequences. Another more general definition is that sustainable development is the simultaneous striving for economic prosperity, environmental health and social wellbeing; the triple bottom line.

The triple bottom line focuses corporations not just on the economic value they add to a community, but also on the environmental and social value they add and destroy. At its narrowest the triple bottom line is a framework for measuring and reporting corporate performance against economic, social and environmental parameters. At its broadest the triple bottom line captures the whole set of issues and processes that companies must address in order to minimise any harm resulting from their activities and to conserve and/or promote economic, social and environmental values. Many corporations today present sustainable practice annual reports in addition to annual financial reports further to the development of international sustainability reporting guidelines (Global Reporting Initiative 2002).

Sustainable practices can be good for business. Unfortunately this means that our industry is embracing sustainable development mostly for promoting social issues as a means of obtaining a license to operate within communities, and is not often addressing some of its significant environmental issues which frequently occur behind closed doors and may not be publicly evident until mining is well underway.

There have now been five International Paste and Thickened Tailings seminars, one a year since the first meeting in Australia in 2000. During that time there has been amazing progress in regard to technology associated with the management of waste tailings produced by the worldwide minerals industry. Understanding and exploiting basic rheology of concentrated suspensions now allows the pumping of high density suspensions, perhaps handling materials with yield stresses in excess of 200 Pascals (a similar thickness to toothpaste), with centrifugal pumps. Great strides in dewatering now allow people to get excited about paste thickeners. Additionally, enough is known about the basic material properties of tailings to know what properties are required for an appropriate disposal strategy. Very high density suspensions of minerals wastes are being used with cement in mine stope fill. A seminar such as this needs to ask itself the question: why preach to the converted? The technology is here now to make dry disposal a reality. Yet the industry continues to pursue unsustainable disposal practices such as riverine disposal and tailings dams. Tailings dams fail on occasions but the argument is always made that it is too expensive to deal with a dry disposal technology up front in most operations; an exception of course is the alumina industry which is making strides towards sustainability.

There are two extremes visible within the mining industry in the public domain. On the one hand, a large and growing number of less-than-world-best-practice examples of liquid waste management are documented in the open literature. On the other hand is the promotion of sustainable development for good business practice. In October 2004 an inaugural Sustainable Development Conference was held in Melbourne sponsored by the Minerals Council of Australia. At the conference it was difficult to see from the program if anyone was dealing with sustainable strategies associated with the liquid waste produced by the industry. The tone of the Sustainable Development Conference was upbeat and positive, conveying that the industry was doing the right thing. Few, if any, of the presenters at this conference even come close to attending a paste technology seminar. What does this mean? It means that the gap between the technology people and the people who actually make disposal decisions is very large. It also means that sustainable strategies associated with waste streams are not being widely promoted and implemented. It is very hard to find new projects today which are moving towards more sustainable practice in tailings management.

Contemplate what current practice really means. Generally, a particular company chooses, for perceived economic reasons and for reasons of commonly accepted practice, to store its waste in tailings dams. An analogy to this is equivalent to living in a house and storing all household waste in the back-yard for thirty, perhaps forty, years and deferring the cost associated with dealing with the waste until forced to do so because of a desire to pass the property to another party. Some would say the minerals industry worldwide is subsidised because often it does not ever have to deal with the direct cost of disposal and rehabilitation of its waste. Virk in 1960 stated, and I quote: "It is interesting to observe that many times more technical effort is devoted to ground water and toxicological studies for abandoned deposits than was ever allocated for the original design and operation." Unfortunately much of the cost for such studies has been borne by government. Should it be surprising that responsible governments are therefore imposing much greater regulatory scrutiny (Hayley 2000).

Pollution and poverty seem to go hand-in-hand. It has been said that new mines will only be opened in inaccessible parts of the world, like the desert and the Arctic, or areas with more lax environmental requirements such as in developing nations. The minerals industry now has the technology to very much improve the way in which it handles its waste, yet the triple bottom line – profit, the environment and society – is hardly ever successfully implemented in the management of mineral waste.

Presented below are some examples of good stewardship and of course a few where people have walked away and got away with it, and a few cases where sustainable practices are far from evident.

For waste minimisation in the minerals industry, it is essential to learn how to dewater and handle suspensions at high concentration. Such materials are non-Newtonian and the industry is now perhaps convinced that it must have some basic understanding of rheology and non-Newtonian fluid mechanics to exploit this behaviour for reducing the volume of waste produced and hence the footprint left by the industry. We have contributed significantly towards this understanding. The purpose of this paper is not to once again speak about technical issues but to plead to all to bridge the gap between those who are responsible for environmental policy and those of us who have to deal with the issues with the waste produced by the industry.

Following the case studies is a discussion of perhaps why industry moves in the direction it does, concluding with a summary of the more recent advances in rheology associated with management of mine waste.

2. Case Studies: Unsustainable and Sustainable

Historically, mining has left a legacy of serious environmental impacts in many countries as the price of significant economic development. Trends towards transnational investments have resulted in consortia of companies and governments turning towards the large unexploited deposits in developing nations such as Indonesia, Papua New Guinea and Chile. However, the hundred-odd intervening years have seen significant technological improvements. The scale of the historical Australian mines is completely dwarfed by that of giants such as Ok Tedi and Grasberg. Grasberg generates in the order of 220,000 dry metric tonnes per DAY of fine particle tailings (Brougham et al. 2003). Most Australian mines would produce less than one week's production at that rate in a year. The environmental price to pay has increased in proportion to the economic benefit derived through mining to the point where it is painfully clear that historical disposal methods used for small scale mining are inappropriate for mining on such large scales. If stringent environmental standards are applied to traditional tailings disposal methods, it becomes uneconomical to continue mining.

Some of the more serious instances of pollution arising from mining have been those where tailings have been discharged into water bodies such as rivers and streams, rather than being impounded: the earliest method of tailings disposal that has long since been rejected by developed nations. In hindsight, it is clear that environmental impacts could have been prevented through improved tailings management. Yet in countries such as Indonesia and Papua New Guinea, large mining companies in recent years have continued to conduct practices such as riverine and submarine tailings disposal even though such practice is known to be unsustainable. Perhaps the best known example is that of BHP Billiton's Ok Tedi mine.

2.1. BHP Billiton's Ok Tedi

A conventional tailings dam was originally planned for tailings storage at Ok Tedi. However, two landslides in 1984 destroyed the initial foundations part way through construction (Wood et al. 2001), also resulting in loss of life (Mineral Policy Institute and AID/WATCH 1999). The shareholders of Ok Tedi decided that mining should proceed using riverine tailings disposal as an interim measure rather than delay the project and lose investor confidence (Jackson 1993, p178). Subsequent geotechnical studies showed that a conventional tailings dam for low concentration tailings could not be constructed safely near the mine (Wood et al. 2001). Riverine tailings disposal continues at Ok Tedi to this day. An agreement reached in 1996 with affected stakeholders requiring dredging of the lower river has proven ineffective in mitigating the environmental impacts, possibly causing additional acid rock drainage (Townsend & Townsend 2004).

Ok Tedi Mining Limited managing director Roger Higgins stated in 1999 that the company had been unable to predict the extent of environmental impact of the mine because the river system was "very, very large" and "largely unstudied" (Anonymous 1999a), even though the adverse effects of riverine disposal at sites around the world have been thoroughly documented. In 1992, the Australian Conservation Foundation reported that the Ok Tedi River up to 70 kilometres from the mine was "almost biologically dead" (Akpan 1998). In 1999, OTML estimated that dieback of vegetation associated with the tailings could cover up to 1350 square kilometres along the Ok Tedi and Fly Rivers (BHP 1999). In 2003, the estimate was increased to 2,400 square kilometres of land that has been, or will be, affected (Ok Tedi Mining Limited 2003). Peak impacts are not likely to occur until 50 years post-mining (Townsend & Townsend 2004), and it may take centuries for the river system to naturally recover. This seems to be sufficient justification to continue riverine disposal at Ok Tedi.

Paul Anderson, the CEO of BHP in 2001 stated that, "the mine (Ok Tedi) is not compatible with our environmental values and the Company should not have become involved,"(WWF 2001). In 1985, BHP wrote off their entire investment in the Ok Tedi project to that date (BHP 1999), approximately A$97 million after tax (BHP 2002). A further A$286 million after tax was written off in June 2001 when BHP transferred its share of assets at Ok Tedi to the PNG Sustainable Development Program Company (BHP 2002). In addition to writing off assets, BHP agreed to provide a repayable funding facility to the Program Company up to a maximum of US$100m and also to purchase copper concentrate in the event of a drought preventing transport along the river. In 1996, BHP also reached an out-of-court settlement with the landholders of the Lower Ok Tedi, resulting in compensation payments of up to Kina 150 million (approximately A$50m) (BHP Billiton). As of 2001 when BHP withdrew from the Ok Tedi project, the company's return on investment was a mere US$66 million (BHP 1999). BHP Billiton has been released from any liabilities arising from the operation of the mine subsequent to the company's departure. Future dividends from BHP Billiton's transferred 52% shareholding will be directed to sustainable development programs. BHP Billiton's involvement in the Ok Tedi mine has therefore cost the company at least A$330 million and the site' environmental issues remain unchanged.

The acting managing director of OTML in 1999, Bill Blenkhorn, stated that it is "most disappointing that the best solution for the people is worst for the environment and vice-versa," (Anonymous 1999b). For the last ten years, Ok Tedi has been responsible for 10% of Papua New Guinea's gross domestic product and for 20% of PNG's export earnings (Anonymous 1999a). PNG has therefore seen significant economic benefit from the mine and the early closure of the mine was not an economically sustainable solution. The development programs and trust funds put in place by Ok Tedi Mining Limited contribute to increasing the social sustainability of the mine although it is difficult to ensure the equitable distribution of trust funds to affected peoples. BHP Billiton have now publicly stated that the company "will not commit to a new mining project that disposes of waste rock or tailings into a river," (Rae 2000): such practice is not environmentally sustainable and may represent a significant future financial liability.

2.2. Freeport-McMoRan's Grasberg Mine

Across the border from Ok Tedi is the Freeport mine located in the Indonesian province of Papua. Rio Tinto own 15% of Freeport-McMoRan Copper & Gold, who in turn own 85.9% of PT Freeport Indonesia (PTFI), the operators of the Grasberg mine commonly referred to as "Freeport." The Indonesian government own 9.36% of PTFI, and the remaining 4.8% is privately owned (Mining Minerals and Sustainable Development 2002). Rio Tinto also have a joint venture agreement with Freeport-McMoRan which gives Rio Tinto 40% of production when production is in excess of 125,000 tonnes per day up to 2021, (Mining Minerals and Sustainable Development 2002) and 40% of all production after 2021(Freeport-McMoRan 2003).

Mining commenced at the site in 1973 with the Ertsberg deposit and is expected to continue at the adjacent Grasberg mine until at least 2041 (Mining Minerals and Sustainable Development 2002). Tailings have been deposited in the Aghawagon River (which discharges into the Ajkwa River) since mining began. At that time, mining was anticipated to last only twenty years, and on a much smaller scale that may have been more appropriate for riverine disposal. The immense Grasberg deposit was discovered in 1988, leading to a thirty-fold increase in throughput at the mine (Mining Minerals and Sustainable Development 2002). Environmental investigations were not performed until the mid-1990's after a blockage in the river forced the evaluation of alternative tailings disposal options (Mining Minerals and Sustainable Development 2002). There is therefore little or no baseline environmental data available for the river or estuary affected by tailings for quantitative or even qualitative analyses of impacts arising from the mine, raising questions as to the efficacy of the Environmental Risk Assessment documents submitted to the Indonesian Government in 2002, intended as evaluation of Freeport's tailings management plan (Freeport-McMoRan 2003).

The Overseas Private Investment Corporation (OPIC) cancelled their political risk insurance of Freeport in 1995, stating that "substantial adverse environmental impacts" had arisen at the site, and further stating that "(had) OPIC....understood that... such unreasonable or major environmental, health, or safety hazards would result (from such high levels of tailings production), the agency clearly would not have issued the...policy" (O'Sullivan 1995), with concern over human rights issues alluded to in subsequent explanations from OPIC (Richards 1996). There are two environmental audits of Freeport publicly available. However, both studies lack independent sampling and scientific analysis, making only general qualitative statements (Ortman & Subra 2000).

Despite the public lessons learned by BHP Billiton at Ok Tedi, Freeport continues to use riverine transport of tailings along the Ajkwa River to an engineered disposal area 90 km from the mine in the lowlands (Freeport-McMoRan Copper

& Gold Inc 2004). 40 km long levees have been constructed at 3km intervals over the 130 square kilometre area designated for tailings disposal (Mining Minerals and Sustainable Development 2002) in order to retain "the majority of the tailings," (Montgomery Watson Indonesia 1999). Tailings currently enter the Ajkwa River at a rate of 220,000 dry tonnes per day (Brougham et al. 2003). It was estimated in 1999 that 5-10% of the suspended solids in the Ajwka river enters the estuary beyond, a proportion expected to increase over time (Montgomery Watson Indonesia 1999). Thus, up to 20,000 tonnes per day of suspended solids, including sulphidic material, enter surface levels of the ocean.

It is difficult to assess the true extent of environmental impacts arising from the presence of Freeport when the Indonesian government makes it notoriously difficult to obtain the required visas for travel to Papua province, and the mine itself is heavily guarded by Indonesian military and by Freeport's own security personnel (Richards 1996). Many of the human rights abuses of the local population reported at Freeport are associated with the army presence rather than with Freeport directly. However, Freeport are "contractually required to provide logistical support for any government official, including the army," (Paul Murphy, Vice-President, Freeport Indonesia (Richards 1996)).

In 1999, Freeport estimated that mine closure costs would amount to US$57.9 million, not including the tailings deposition area (Montgomery Watson Indonesia 1999). Freeport used a consultant in 2003 to estimate that total final rehabilitation and reclamation costs will be in the order of US$130 million, but claim that ultimate rehabilitation of the site will be "based on applicable laws and regulations and our assessment of appropriate remedial activities in the circumstances after consultation with governmental authorities, affected local residents and other affected parties"(Freeport-McMoRan 2003). There is no technical description of the rehabilitation plan for the tailings deposition area available in the public domain. For the years 2001-2003, an average of around US$70 million was spent annually on "environmental capital expenditures and other environmental costs" such as levee maintenance within the tailings impoundment area and partial rehabilitation (Freeport-McMoRan 2003). As of 1999, monitoring and maintenance costs were anticipated to total US$1.6 billion "for mine life" (Montgomery Watson Indonesia 1999), yet there is seemingly no provision for any monitoring and maintenance after closure, and acid mine drainage is expected to eventually cause a significant problem at the site.

Rehabilitation is to be performed at the completion of the Grasberg pit with funding from a cash trust fund of US$100 million to be accrued during operations as a condition of the reinstatement of political risk insurance from OPIC. Any additional costs for rehabilitation are to be funded by operational cash flow or future operations (Freeport-McMoRan 2003). Indeed, Freeport (with Rio Tinto holding a 40% interest in any future exploration) intend to continue mining in the Papua area long into the future ("for the next century," according to Freeport-McMoRan president George Mealey in 1996 (O'Neill 1996)), presumably continuing to use riverine disposal since it is apparently the "most appropriate management system for the site conditions," (Freeport-McMoRan Copper & Gold Inc 2004) "...[representing] the best alternative, considering the applicable geotechnical, topographic, climatological, seismic and water quality conditions," (Montgomery Watson Indonesia 1999), where "best" clearly means "most economic". If mining is to occur in the area for the next century, it may well be worth the investment in an alternative, more sustainable disposal strategy such as thickened disposal transport to lowlands.

Freeport has endeavoured to investigate alternative tailings storage schemes such as marine disposal, highland disposal or pipeline transport to lowlands. The cost of implementing submarine disposal was estimated by Indonesia's Minister for the Environment at US$3 billion (Anonymous 2003), with most of the cost presumably consisting of pipeline construction to the lowlands although there is no publicly available breakdown of the $3b estimate. In 1999 Freeport gained permission from the Indonesian government to increase ore throughput capacity to 300,000 tonnes per day. There have been several slippage incidents at the mine, one resulting in eight deaths (Freeport-McMoRan 2003), attributed to the high rate of mining. Mining at a reduced rate has seemingly not been presented as an option despite the obvious environmental advantages (Ortman & Subra 2000).

The Grasberg mine produces the lowest-cost copper in the world (Freeport-McMoRan). In 2003, total production costs were 13.6 cents per pound of copper (including 1.2 cents per pound for reclamation "and other" costs and including gold and silver credits), resulting in a gross profit of 71.1 cents per pound of copper (Freeport-McMoRan 2003, p28). Freeport's revenues for 2003 were US$2.2 billion (Freeport-McMoRan 2003, p25). The CEO of Freeport Indonesia is personally remunerated to the order of US$40 million per year (Bryce 1997). Freeport Indonesia are responsible for almost 2% of Indonesia's GDP, 58% of Papua's GDP, and the multiplier effect of Freeport's presence in Indonesia totalled an estimated US$30 billion of economic benefit from 1992 to 2003 (Freeport-McMoRan Copper & Gold Inc 2004). Freeport are frequently the largest taxpayer in Indonesia, paying US$329 million in taxes and royalties in 2003 (Freeport-McMoRan 2003). The mine continues to press on towards economic sustainability: Indonesian transmigratory programs are populating the low-land areas in anticipation of extensive mining activity in the future, yet the area's social sustainability is dubious since the indigenous population largely do not gain employment at the mine because they are less educated than the Javanese immigrants. The "best" solution for tailings disposal at Freeport Indonesia is riverine disposal because it costs next to nothing, despite its environmental unsustainability.

Thickened tailings or paste disposal is often not considered in areas where water is abundant such as in the case of equatorial mountain ranges. The advantages of more stable, readily consolidating, easily rehabilitated tailings storage facilities created with high yield stress tailings are overlooked. Dewatering yields a lower volume of tailings that reduces transport costs, covering a smaller footprint in lowland areas. Thickening tailings may even lend itself to submarine disposal in areas of appropriate undersea topography. However, submarine tailings disposal is still a contentious issue and preliminary forays have produced mixed results, as the following example illustrates.

2.3. Rio Tinto's Lihir Mine

The Lihir Gold Mine is located on Lihir Island in Papua New Guinea and is managed by the Lihir Management Company, wholly owned by Rio Tinto. Rio Tinto own 75% of Southern Gold, who are 22.9% shareholders in Lihir. Other shareholders include Nuigini Mining, Lihiran Trust (landowners) and the PNG Government through Orogen Minerals (Mineral Policy Institute). Lihir commenced operations in 1996 (Jones & Gwyther 2000).

The Lihir mine utilises "submarine" tailings disposal which to date has involved discharge into waters of Louise Harbour at a depth of 125 m (Jones & Gwyther. 2000). Lihir is expected to discharge a total of 89 million tonnes of tailings and 330 million tonnes of waste rock into the sea (Mineral Policy Institute) at a rate of 8000 tonnes per day (Jones & Gwyther 2000). The discharged tailings contain unneutralised cyanide and are clearly visible in the bay in satellite images (Mineral Policy Institute) indicating that a significant quantity of tailings is dispersing in a horizontal plume rather than descending to the sea floor (Mineral Policy Institute 1999). The Lihir Prospectus of 1995 stated that seven kilometres of coral reef are anticipated to be destroyed by the tailings in a "severe impact zone". Whilst the processing circuit at Lihir involves pressure oxidisation of the sulphide ores (the majority of mined ore at Lihir) (Mining Technology 2004), any sulphides in the tailings that remain in the oxygenated surface zones present a threat to the environment (Mineral Policy Institute 1999) by increasing the bioavailability of metals found in tailings.

The Lihir project was denied political risk insurance by OPIC; "it could not support the project based upon initial concerns about US environmental policy regarding ocean discharge of wastes" (Overseas Private Investment Corporation 1995). However, Australia's Export Finance and Insurance Corporation (EFIC) do not have "any clear organisational standards or guidelines relating to...environmental impact assessment," (Mineral Policy Institute and AID/WATCH 1999) and in conjunction with Rio Tinto reviewed the London (Dumping) Convention of 1972 and subsequent amendment of 1996 in the context of submarine tailings disposal. EFIC and Rio Tinto concluded that that the Convention does not apply to pipe discharges, does not specifically refer to mine waste, and EFIC agreed to provide A$250 million of political risk insurance for Lihir (Mineral Policy Institute), paving the way for subsequent operations opting for submarine tailings disposal.

In 2003, Lihir Gold paid a total of US$22 million in taxes and royalties and US$13 million in salaries to PNG nationals (Lihir Gold Limited 2003b), recording a total profit of US$35 million (Lihir Gold Limited 2003a). Whilst not environmentally ideal, submarine tailings disposal could perhaps be improved on by further dewatering of tailings before disposal to ensure that the tailings descend to the sea floor rather than dispersing in surface waters.

2.4. Impoundment Failures

The conventional tailings dam was developed as an alternative to riverine tailings disposal, where topography and geotechnical conditions permit. There is an inherent risk associated with storage of unconsolidated tailings due to the amount of water retained within the tailings. Seepage can result in groundwater or receiving water body contamination, or operational mismanagement can lead to wall failures or overtopping. There have been on average five tailings impoundment failures per year since the 1980s (Mining Journal Research Services 1996): all could have been avoided through the used of paste or thickened tailings technology.

One of the more notorious tailings impoundment failures is that of the Los Frailes Tailings Dam in Aznalcollar, Spain, in April of 1998. The lead-zinc mine was purchased by Boliden in 1997. The last full-scale stability investigation of the paddock-style tailings dam was undertaken in 1996. The dam was filled to half of its design capacity of 33 million cubic metres when a fault in the marl 14 metres below the dam due to surplus interstitial water caused a 600 foot section of the dam wall to slide 60 metres. An estimated 5.5 million cubic metres of tailings flowed up to 40 kilometres down a river, covering 2600 hectares with tailings of pH 2.9. Total cleanup costs were US$227 million, requiring the return of 500,000 truck loads of contaminated soil to the mine (Eriksson & Adamek 2000).

Tailings impoundment failures frequently result in direct or indirect loss of life. There were five lethal traffic accidents during the cleanup following the Los Frailes failure. The most recent documented incident of deaths resulting in loss of life was at the Rio Verde mine in Brazil in 2001.

At the Rio Verde mine, tailings were deposited at low concentration in a mined out pit to a depth of 100 metres over a seven year period (Nicolau 2001b). The side of the pit 40 metres from the top failed (Eponine et al. 2001), taking the lives of five workers (Freitas 2001). The tailings flowed for 6 kilometres downstream (Gontijo 2001) at depths of up to 10 metres (Odilla & Portela 2001), taking 12 hours to control the spill (Nicolau 2001a). 100,000 people were left without water following the incident (Rezende & Santos 2001). The water catchment area for up to 70% of the Belo Horizonte area may have been contaminated (Gontijo 2001). The Mineração de Rio Verde were fined R$1.5 million following the incident and are liable for R$50,000 per hectare of contaminated catchment area or ecological reserve (Freita et al. 2001). The fines and any reclamation, in addition to wages for 160 local people, cannot be financed by the company unless operations continue (Odilla & Portela 2001).

Most tailings impoundment failures occur at operating mines. However, there are long term environmental impacts arising from tailings impoundments containing unconsolidated tailings; all tailings dams seep as part of the consolidation process. When tailings impoundments are abandoned through bankruptcy, or historically because of no rehabilitation requirement, there is potential for pollution due to unmanaged seepage.

A long history of small scale mining has left the number of abandoned tailings dams world wide in the tens of thousands (United Nations Environment

Programme 2001). In China, 2 million hectares of land are covered with mining waste (United Nations Environment Programme 2001).

Increasingly stringent requirements for mine planning and operation decrease the rate at which abandoned tailings dams are accruing, however company bankruptcies continue to occur which result in orphaned dams. For example in Nevada over the past four years, at least ten mining companies have declared bankruptcy, leaving taxpayers remediation bills of over US$270 million (Great Basin Mine Watch 2002).

2.5. Piney Point – Mulberry Phosphates

The Piney Point Phosphate Plant and its associated tailings impoundments (known as phosphogypsum stacks) were abandoned in 2001 due to the bankruptcy of its operator, Mulberry Corporation. In addition to the contamination of the underlying aquifer due to the absence of stack lining, there is a significant risk of overtopping in the event of heavy rainfall. There are 452 hectares of phosphogypsum stacks to be rehabilitated at Piney Point (United States Environmental Protection Agency 2003). As of November 2002 it was estimated that 1.9 billion gallons of wastewater, stack seepage and runoff must be removed in order to close the Piney Point site (Florida Department of Environmental Protection 2002).

Piney Point is expected to cost a total of US$140-$160 million to close (Florida Department of Environmental Protection 2003; O'Horan 2003; Parsons 2003; Pittman et al. 2003; United States Environmental Protection Agency 2003). The Florida Department of Environmental Protection spent US$40 million in the first two years of managing the Piney Point site (United States Environmental Protection Agency 2003), and a further US$45 million was authorised in a Florida Legislative session to fund ocean dispersal of treated surplus water and the aggressive pursuit of closure at the Piney Point and Mulberry sites (Florida Department of Environmental Protection 2003). Funding will exhaust the Non-Mandatory Land Reclamation Trust Fund (Parsons 2003), a trust established through phosphate taxes intended for rehabilitation of phosphate mining-affected lands throughout Florida.

Other examples of companies abandoning mines include the Kam Kotia mine in Ontario, Canada, leaving 6 million tonnes of acid-generating tailings and a bill of over US$40 million (Cowan & Robertson 2001); the Giant mine in British Columbia with a US$250 million legacy (Trerice 1999); the Summitville mine in Colorado leaving a bill of over US$100 million (United States Environmental Protection Agency); and the Yerington mine in Nevada which will cost taxpayers over US$270 million to rehabilitate (Great Basin Mine Watch 2002). Estimates by the Mineral Policy Center put total US mining-related environmental cleanup costs at anywhere between US$32 and $72 billion (Mineral Policy Center and Taxpayers for Common Sense 2001), with tailings impacts constituting a significant portion of the liability.

Even when properly managed, conventional tailings dams still represent a long-term liability for mining companies. Rehabilitation is difficult until consolidation occurs, a process that can take many years. The dam structure must be continually monitored for stability in the interim. The mining company responsible for the tailings facility may therefore not be able to sign off on a site for decades after operations have ceased. The increasing magnitude of environmental sureties may mean that significant capital is tied up in sites that no longer yield any income but may not yet be successfully rehabilitated. In many instances where a conventional tailings dam is considered, a thickened or dry disposal facility is likely to be a feasible option for disposal.

2.6. Alcoa – Hedges Gold

The conventional tailings dam at Hedges Gold is an example of good company stewardship and proper operation of a tailings facility. Hedges Gold is a subsidiary company wholly owned by Alcoa (Jarvis 2004). 1.3 million ounces of gold were extracted at Hedges over an 11 year period (Jarvis & Hatch 2001). The tenement rights for the Hedges mine worked areas and part of the exploration license were acquired by Boddington Gold Mine in 1998 (Jarvis 2004). Boddington is thought to be one of the world's largest undeveloped gold deposits, with an expansion of up to 190,000 tonnes of mined ore per day intended to commence production in 2006 (Newmont Mining). The freehold areas of the Hedges site were retained by Alcoa, incorporating the tailings disposal area (Jarvis & Hatch 2001). The environmental liability for the tailings therefore remains that of Alcoa. Tailings were deposited on site in a conventional tailings dam constructed as a valley fill using the downstream raise method (Jarvis & Hatch 2001), considered to be one of the more sound methods of embankment construction. The tailings cover approximately 170 hectares (Jarvis & Hatch 2001). The nature of the tailings impoundment meant that erosion was the main concern; extensive slope flattening has been performed in addition to revegetation. The plants atop the 100 mm topsoil capping layer are able to access the benign water held within the tailings. Some areas of the Hedges mine were within State Forest or were forest blocks within neighbouring Hotham farm; these have been revegetated and integrated into the adjacent jarrah forests (Jarvis 2004). Gradual financial provision was made during the operational phase of the Hedges project for performing rehabilitation at the end of operations (Jarvis & Hatch 2001).

Runoff from the site will comply with the requirements of the Western Australia Department of Environmental Protection as well as trigger values determined by local community groups which stipulate that cyanide levels should not be above detectable limits. In the interim, underdrainage water is returned to the tailings storage area, where surface water runs to a holding pond and is then discharged after treatment. Alcoa, through extensive community consultation, are in the process of obtaining permission to discharge untreated water into the Hotham River, with trial releases occurring mid-2004. The tailings dam will be rehabilitated over a period of up to ten years and it is projected that the tailings dam will ultimately be a self-sustaining system (Jarvis 2004).

It may have been possible through the use of dewatered tailings at Hedges to significantly reduce the amount of seepage water from the tailings and to recover cyanide for use in the processing circuit during the operation of the mine.

2.7. Alumina Industry Dry Stacking

Arguably the most successful implementation of tailings thickening has been within the alumina industry, which has led the world in innovative tailings disposal methods through dry stacking of red mud residue. The alumina industry is now progressing in carbonation of red mud residue to reduce alkalinity of seepage water (Cooling et al. 2002). Space constraints and the desire for increased process caustic recovery have necessitated innovative disposal methods that minimise the footprint for tailings as well as facilitating containment of environmental impacts. The result has been the maximisation of residue storage within a given space in an inherently stable structure that can be rehabilitated as soon as deposition ceases.

3. EXPLOITING RHEOLOGY IN TAILINGS WASTE MINIMISATION

We have written many papers in this area now, ranging from titles such as 'Procrastination may not pay in tailings management'(Ruse & Boger 2003) to 'Sustainability, environmental rheology and full cost accounting of tailings disposal'(Ruse et al. 2003), to papers specifically on the technical aspects of exploiting rheology in tailings management (Sofra & Boger 2002). A complete biographical list is available from the second author.

In the management of tailings waste it is not only important to remove the water to decrease the footprint, and possibly move from wet to dry disposal strategies, but also from the point of view of recovery of water. Water is and will become a big issue worldwide where countries like South Africa and others will increase the cost of water and make it more important to have a much better water balance in these processes.

Technology exists now, in any green field site, to move to a strategy like that one shown in Figure 1, and reinforced in Figure 2.

3.1. What Type of Tailings Strategy is Required?

Having established the type of tailings disposal strategy that is required, whether it be thickened tailings disposal, dry stacking, or paste backfill, we now do know what sort of rheological characteristics of the suspension are required. This then feeds back into the pumping system and allows one to develop the strategy required for pumping. For example, rules of thumb do exist and the current thinking is that materials up to a yield stress of 200 Pascals can be handled with centrifugal pumps (Shook 2004). The industry almost invariably avoids the use of positive displacement pumps due to the argument that they are not economical; this may not be the case since lower pumping velocities result in decreased pipe and pump wear and require less pumping energy.

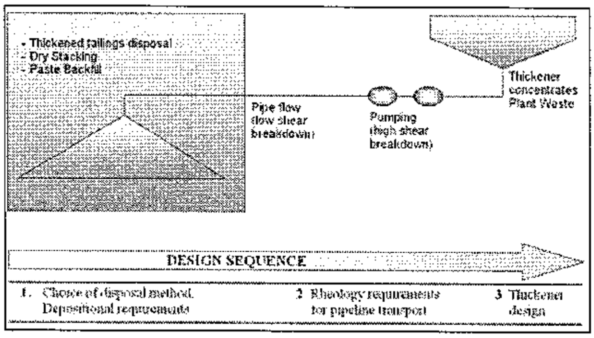


Figure 1: Suggested approach for determination of tailings disposal system.

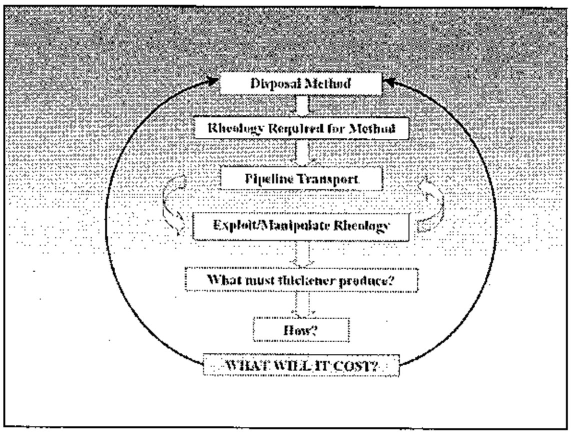


Figure 2: Design and implementation strategy.

Going back from the pumps takes us to the way in which the material is dewatered. Technology now exists for laboratory measurements to be made to evaluate the ease with which a material can be dewatered and to examine the influence of flocculation on the dewatering process; these same measurements can be used to predict consolidation in the ultimate tailings strategy (de Kretser et al. 2003).

Added to this process, in Figure 2, is the ability to exploit and/or manipulate rheology which is often related to surface chemistry. Exploitation through surface chemistry management will become more important in the future as we move more and more towards dewatered tailings. Cost then enters the equation, but the accounting practices used these days often consider only the immediate processing cost, and capital cost, and do not consider environmental implications and/or the cost of storage and rehabilitation at the end of the day.

Financial accounting requirements are changing to require a full estimate of environmental liability costs as soon as the costs are incurred and for the liability to be immediately included in the balance sheet (Financial Accounting Standards Board 2001). The USA is currently the only country with powers to pursue environmental remediation costs from previous owners at abandoned sites. There is therefore a worldwide trend in environmental surety legislation requiring mining companies to estimate their environmental liabilities and lodge a corresponding amount as a bond. There is thus an increasing requirement to calculate what the final cost of rehabilitation will be and therefore a drive to reduce the magnitude of that *total* cost from the outset, not merely the initial capital and operating costs. The mining industry will see a gradual realisation of the true cost of dealing with waste, with the only accepted alternative being to pay more to a third party to treat the waste generated in the mining industry.

The attitude associated with mineral processing expressed in Figure 3 is no longer acceptable. Tailings is a product which has a significant negative cost associated with it, and it is prudent to tackle this cost head on through innovation in tailings management.

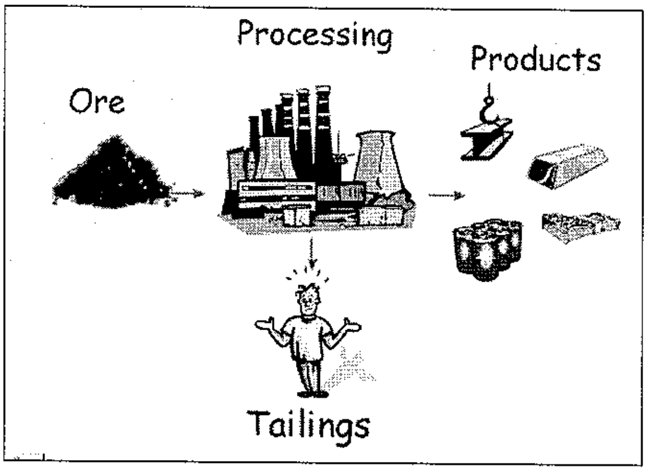


Figure 3: This attitude will not prevail.

The yield stress is the most important parameter required in the design of disposal strategies. Paste backfill, which is often gravity fed back into the mine stope, can have yield stresses exceeding 500 Pascals. Dry stacking employs materials with yield stresses on the order of 50-100 Pascals, and thickened tailings generally utilises materials which just begin to show the presence of a yield stress where the value may be of order 2 Pascals. The best way to measure the yield stress is with the vane technique, illustrated in Figure 4. The technique is a simple, single point determination which eliminates slip, which is a problem in standard rheometry, but is limited to yield stresses in excess of about 10 Pascals. Basically the vane is inserted into a sample, is rotated at a slow speed and the peak in the torque time curve is measured and interpreted in terms of a simple equation defining the yield stress (Nguyen & Boger 1983; 1985).

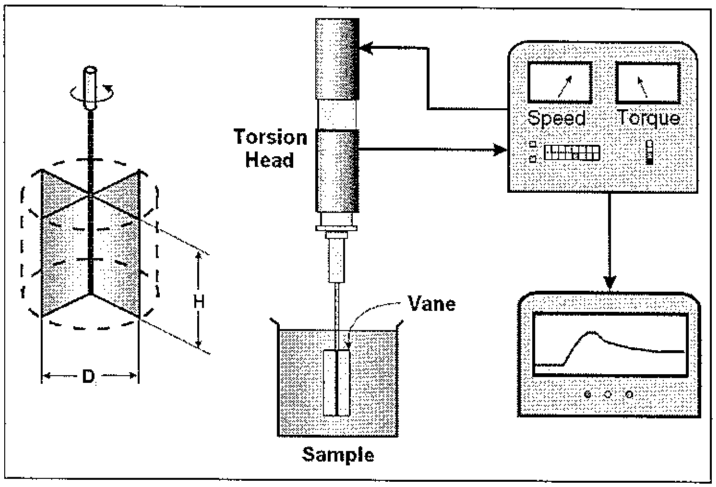
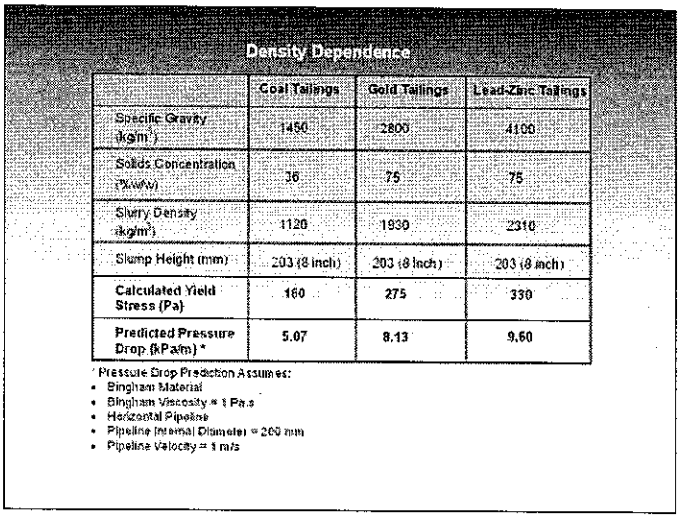


Figure 4: The vane technique.

The slump test which is traditionally used for paste backfill or mine stope fill is not a useful number for comparative purposes across different industries if the slump is measured with the standard conical technique and interpreted in terms of slump in inches or centimetres. However, with correct interpretation the yield stress determined from the slump as measured with a *cylinder* agrees very well with the yield stress measured with the vane technique (Pashias et al. 1996; Clayton et al. 2003). Figure 5 shows the slump height versus yield stress for a coal tailings, a gold tailings and a lead zinc tailings. Each exhibited the same slump of 203 mm (8 inch), yet the true yield stress for the three materials varies respectively from 160 for coal tailings, to 275 for gold tailings, to 330 for lead zinc tailings. If this slump height was used and the materials all had the same plastic (Bingham) viscosity, the shear stress-shear rate curves for the three materials would be identical. However, the tailings all have vastly different yield stresses (see Figure 6). The industry should be moving away from the traditional conical slump test technique to the simpler and more realistic "tin can".

Extrapolation of measurements of shear stress versus shear rate, which is often done from measurements obtained in a concentric cylinder device, can lead to serious error and sometimes catastrophic effects in a new process. There are two sorts of problems encountered here; one is the potential for slip flow, the other is that the data in a non-slip situation at low shear rates in a concentric cylinder can be flawed. Concentric cylinder rheological measurements are often used for pipeline design when the material is approximated with a Bingham plastic model. Such a model can be appropriate if one does not pay attention to the low shear rate data and, we believe, can be effective for turbulent pipeline design. An issue in the future which is still not resolved is, how do we deal with sedimentation in the pumping of high density suspensions in laminar flow, as occurs when using positive displacement pumps.

Note that we do not use the term "concentration" very often because it is the yield stress not the concentration that is the important variable.



Density Dependence

	Coal Tailings	Gold Tailings	Lead-Zinc Tailings
Specific Gravity (kg/m^3)	1450	2800	4100
Solids Concentration (%w/w)	36	75	75
Slurry Density (kg/m^3)	1120	1930	2310
Slump Height (mm)	203 (8 inch)	203 (8 inch)	203 (8 inch)
Calculated Yield Stress (Pa)	160	275	330
Predicted Pressure Drop (kPa/m) *	5.07	8.13	9.60

* Pressure Drop Prediction Assumes:

- Bingham Material
- Bingham Viscosity = 1 Pa.s
- Horizontal Pipeline
- Pipeline Internal Diameter = 200 mm
- Pipeline Velocity = 1 m/s

Figure 5: The yield stress for materials with the same slump.

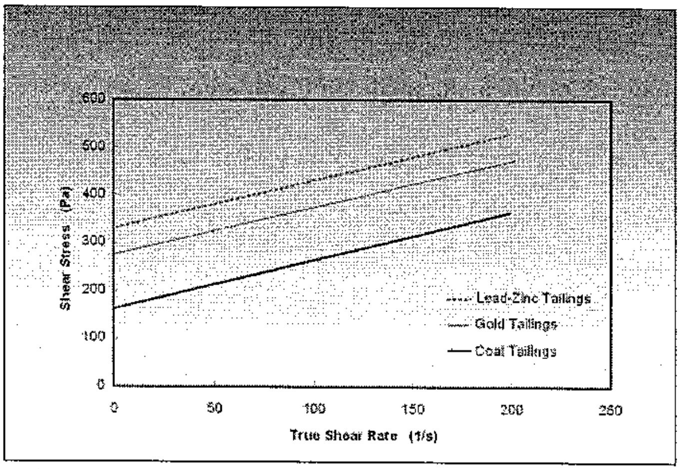


Figure 6: Bingham curves for three materials with an 8 inch slump height (assuming a Bingham viscosity of 1 Pa.s).

Figure 7 shows some typical yield stress concentration data for a manganese tailings, a nickel tailings and a copper tailings. One can determine the concentration of the particular tailings for a particular operation. For example, the concentration for each suspension to generate a material with a yield stress of 100 Pascals is illustrated on the diagram. This concentration ranges from about 40% for the manganese tailings up to 62% for the copper tailings. Concentration means little in establishing the conditions for construction of a material for dry disposal. There are many materials where the yield stress concentration curve turns upward exponentially at significantly lower concentrations; this is particularly true in clays which are a major issue in tailings disposal, and in materials that have high aspect ratio particles present, which can be the case with lateritic nickel ores. Data of the type shown in Figure 7 is the essential first step in examining a disposal strategy.

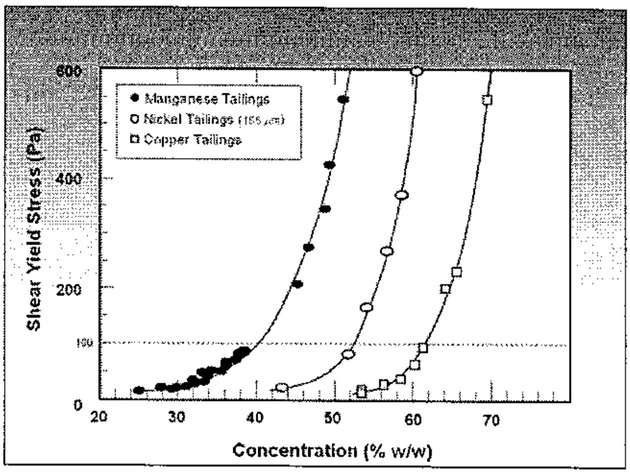


Figure 7: Comparison of the yielding characteristics of a variety of mineral tailings systems.

In terms of dewatering devices laboratory techniques are now available to measure the compressive yield stress and the permeability as a function of concentration (de Kretser et al. 2003). These parameters are not significantly different from the conventional measurements made by the geotechnical engineers and used for consolidation predictions in dams but have been put in a generalised framework which allows such results to be used fundamentally in the design and evaluation of thickeners and filtration devices. Additionally, such laboratory measurements allow the influence of flocculants on compression to be measured.

The bottom line in all of these arguments is that the technology really is now available to dewater and handle minerals tailings at significantly higher concentrations than is the current practice. The alumina industry is a classical example of implementing such strategies. We have been involved with Alcoa of Australia, where great strides have been made, since the 1970s. Currently the work of David Cooling is exploring the contact of red mud with stack gas. The net result is a reduction in the pH of the tailings to such an extent that biological activity can be encouraged which allows the carbon in the tailings streams to be dealt with, producing more CO_2, and ultimately if implemented, may result in a significant improvement in the process. More sustainable practices associated with the handling of the tailings waste produced by the minerals industry may in fact be good business. Certainly we firmly believe that the industry needs to be proactive in dealing with these waste issues before it is forced to do so by legislation and/or environmental controls. It is clear "environmental considerations dictate that we must manipulate tailings to fit a particular environment rather than manipulating the environment to contain the tailings"(Sofra 1999).

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