

Consideration of ARDML risk as part of process flow sheet development

S.Pearce^A, D.Brookshaw^A
S.Mueller^B
H.Kaasalainen^C
H.Purnamasari^D

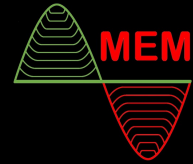
^A Mine Environment Management, 3A Vale St,
Denbigh, Wales, UK, LL16 3AD

^B Boliden Mines, Boliden, Sweden

^C Sweco Industry Oy, Turku, Finland

^D PT Agincourt Resources, Sumatra Utara, 22738

BC MEND ML/ARD ANNUAL WORKSHOP



The Science Behind Success

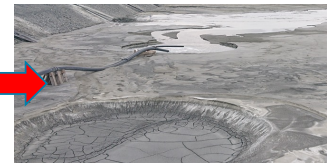
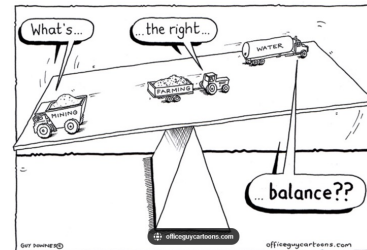


Mine Environment Management Ltd

www.memconsultants.co.uk

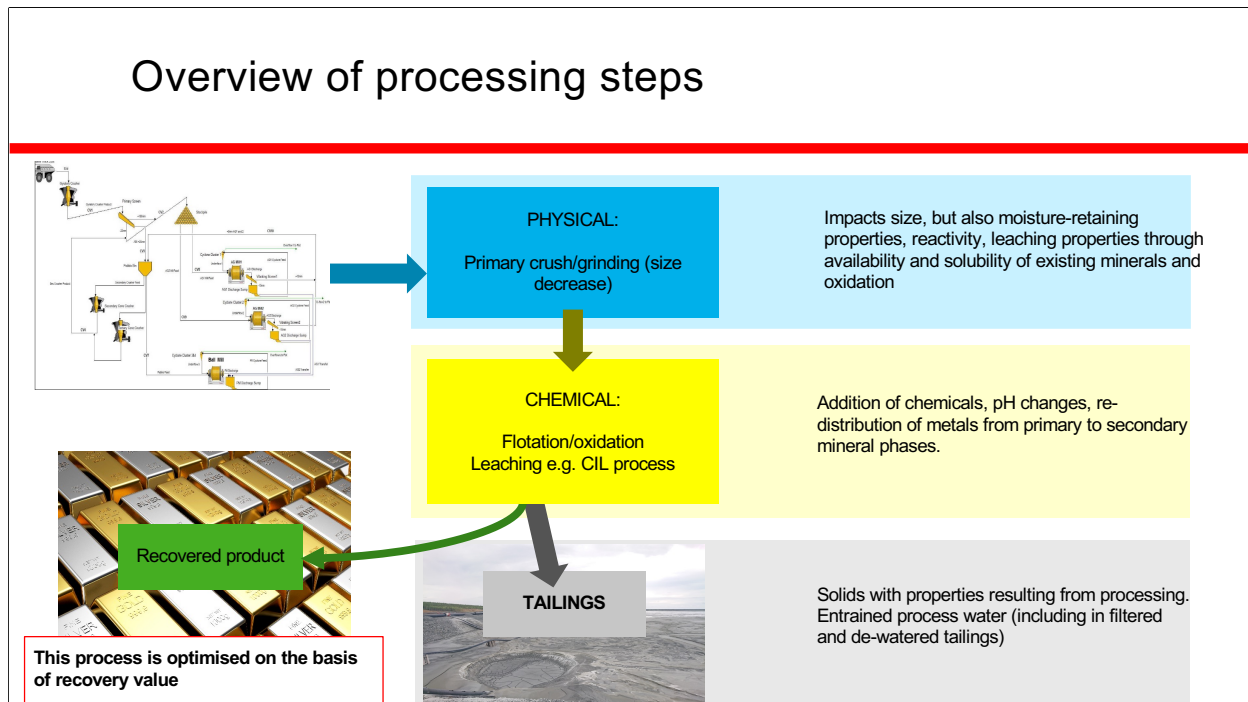
Introduction

- Processing is driven by the optimisation of recovery, closure liability is an unintended but unavoidable consequence
- Processing affects geochemical and geotechnical properties of tailings
- Processing directly impacts on the short and long-term liability from tailings BUT rarely considered in detail when process flow sheets are developed
- Take holistic (balanced) approach to consideration of the geochemical and geotechnical properties of tailings



Notes: The process is focused to optimise recovery of targeted metals. Many of us may have experience at sites where short term recovery rates are measured as KPIs that can in many cases affect the employees' quarterly or annual pay bonuses. The processing steps directly affect sulfur and metals within the tailings, including secondary minerals, which can pose long term AMD risks, such as gypsum, produced during processing result in long term AMD leaching. The resulting solutions include highly engineered and expensive cover systems. The physical properties of the tailings can also increase costs as engineering complexity increases with finer texture and lower strength tailings.

As the controls and cost increase, an opportunity exists when designing the processing flow sheet, to balance maximising recovery on the one hand and creating tailings with properties that do not hinder geotechnically or geochemically their disposal and long-term stability. Thus, Optimisation of Process Flow and Metallurgy to Reduce Risks from AMD in Tailings and recover critical metals offers several opportunities.



Notes: So what are the common processing stages and what impacts can they have. The processing will follow a set of steps, which can be complex and repeat stages or cycle until the required recovery is achieved. We have simplified the process here. Initially, the rock is crushed and ground to release the metal-bearing minerals and increase the surface area to maximise reaction rates. This physical processing step determines to a large degree the geotechnical properties of the tailings as well.

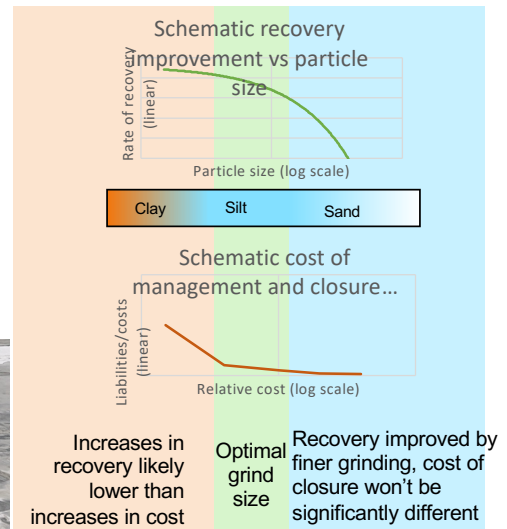
Particle size also affects the geochemical behaviour of the tailings, in terms of reactivity and leach properties. And at this stage, oxidation of sulfides in the tailings is also occurring as grinding is carried out in the presence of air. We will discuss the change in geochemical properties with changing particle size in more detail later on.

Following this, generally are flotation stages where chemicals are added to separate the ore-bearing particles. If the target metal is hosted in sulfides, processing could include oxidation. Leaching steps can include pH changes or addition of complexing agents such as cyanide. Once the concentrate is separated, the remaining material constitutes the tailings. The rock that becomes the tailings is the product of the recalcitrant part of the ore-bearing rock and the cumulative effect of all the processing steps, leading to potentially fundamental reorganisation of the minerals and metals. The product will be site-specific in the same way that the process flows and ore rocks are.

Despite this vital role that processing plays in the end tailings product, processing is optimised on the basis of recovery value rather than cost to achieve closure objectives.

Grinding size and “integrated” cost curve

- Particle size affects hydrological and geotechnical properties including plasticity, strength, permeability, density
- Operational management and closure engineering can be very challenging if the tailings are “soft”
- Size is a physical property, but has impact on geochemistry
- Finer grainsize in many cases increases risk/liability/cost of management and therefore requires considering alongside recovery as a key metric as part of optimising process flow



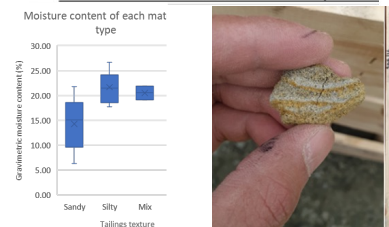
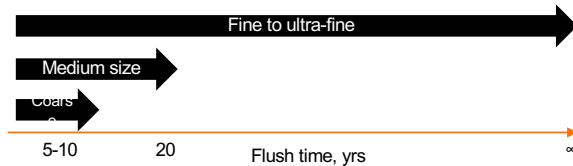
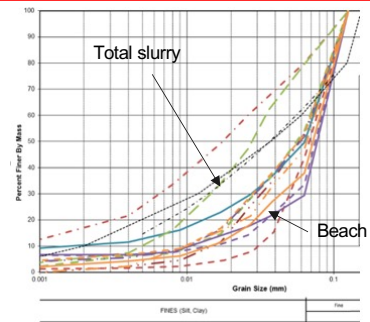
Notes: Let's take particle size in the first instance.

As mentioned, ore is initially ground and milled. This increases the rates and efficiencies of reactions with flotation chemicals, therefore this step aims to achieve an optimally-fine product to maximise ore recovery. However, as grain size decreases and the tailings become silt- or clay-sized (also referred to as fine and ultrafine), their geotechnical properties become more challenging – for example, the strength of the materials decreases, particularly if they are placed as a slurry.

The risks and costs associated with constructing safe tailings dams and closing them are not generally considered when grind size is decided, however, the gains in recovery can be relatively small when compared to the additional challenges that have to be overcome as the tailings size decreases. If we consider in a theoretical way the recovery increase that can be achieved as particle size decreases a plateau is reached, where improvements in recovery decrease as limitations in other parts of the process flow take over. Conversely, with the increasing geotechnical and geochemical challenges posed by fine tailings, a relatively small change in particle size of the tailings can have a very significant impact on the cost of managing this waste.

Particle size and geophysical properties

- We can observe the effects of particle size in slurry tailings because hydrodynamic separation from spigoting causes particle segregation – different properties in beach vs pond
 - Beach areas = coarser particles (higher k, lower porosity)
 - Pond area = finer particles (lower k, higher porosity)
- Beach areas are prone to quicker draindown = improved geotechnical condition and faster flush times for pore water but dry conditions and possibility for oxidation and weathering
- Pond areas may have slower draindown = challenging geotechnical condition and greater flush times for entrained process water
- A very long time may be required to exchange the pore water entrained in finer tailings due to lower k and higher water content

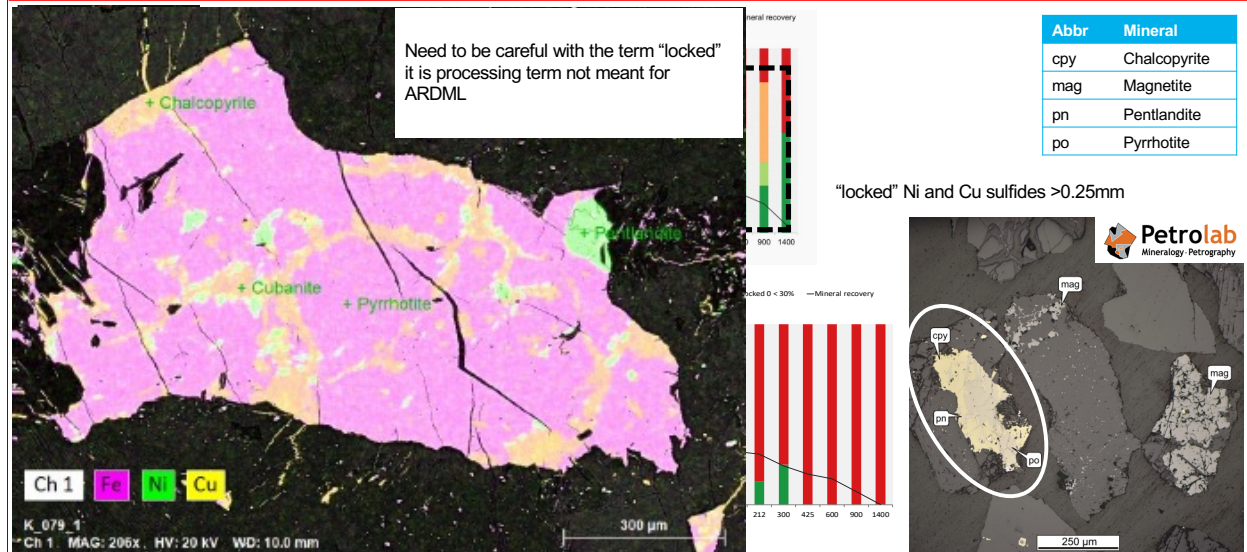


Notes: We can observe the effects of particle size in slurry tailings because hydrodynamic separation from spigoting causes particle segregation. This results in coarser tailings being deposited at the beach of the tailings facility compared to the pond. You can see this on the particle size distribution plot where in black is the total slurry result and in colour the results of samples recovered from the tailings facility beach during a drilling program. You can see that the majority of samples recovered from the tailings facility have a coarser texture than the slurry itself, owing to this segregation effect.

This leads to different properties in the beach area of a tailings facility compared to the pond. At the beach, the coarser particles lead to higher permeability and lower porosity. This means that beach areas are prone to quicker draindown leading to improved geotechnical condition and faster flush times for pore water. Conversely, however, this means that tailings in the beach area are more at risk of experiencing oxidation and weathering as they become unsaturated.

Since pond areas tend to have finer particles, the hydraulic conductivity is lower leading to slower draindown. The higher porosity in the finer particles leads to higher moisture content. This creates challenging geotechnical conditions and greater flush times are required for the entrained process water.

Particle size and mineralogy

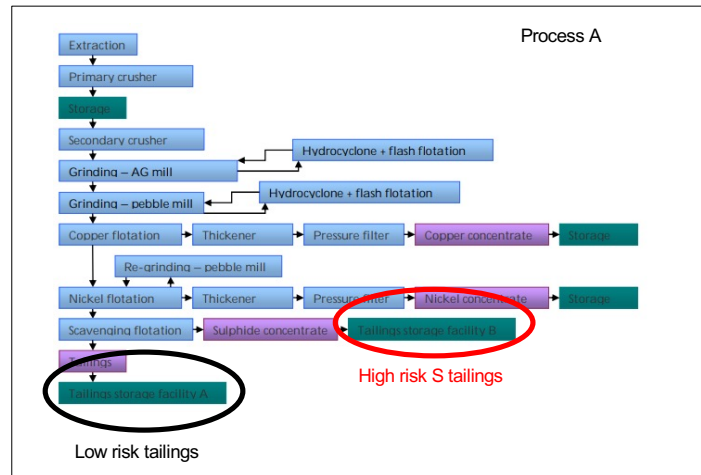


Notes: These two images show the 250 micron sized fraction material. At this size the sulfides (shown in this figure) remain locked or partially locked, while the carbonates are liberated.

The charts show that the liberation profile for the carbonates is relatively evenly distributed across the particle size range but for the sulfides the size fractions >100 um are much less well liberated and are described as "locked".

Case Study A: Overview

- Ore minerals: chalcopyrite (Cu ore) and pentlandite (Ni ore) = process in two steps
- Two types of tailings; lower risk (main); and high-risk sulfide tails
- Low risk tailings: neutral pH, nickel, cobalt and copper present
- Drainage quality is affected by Ni, Co and sulfate as they are mobile in circum-neutral pH



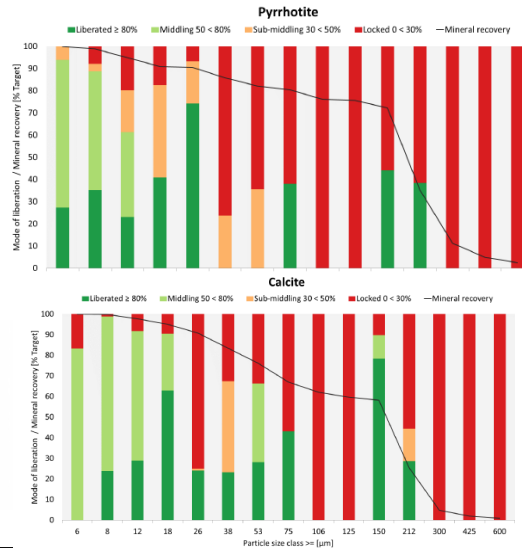
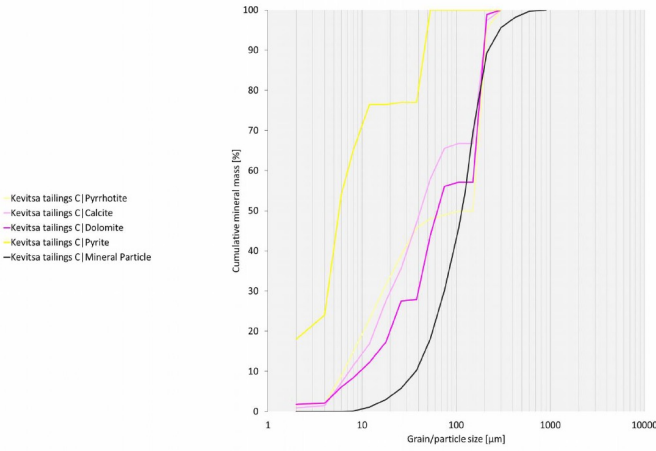
Notes: For the geoscientist out there, Case study A is a base metal, nickel-copper-platinum group element in ultramafic rock.

The economic mineralisation occurs as disseminated Cu and Ni sulfides. The ore sulfides mainly **chalcopyrite** (kal-ka-pyrite) and **pentlandite** (pent-lan-dite) are targeted by processing as shown on the right. Some residual iron, nickel and copper sulfides remain in the low sulfur tailings.

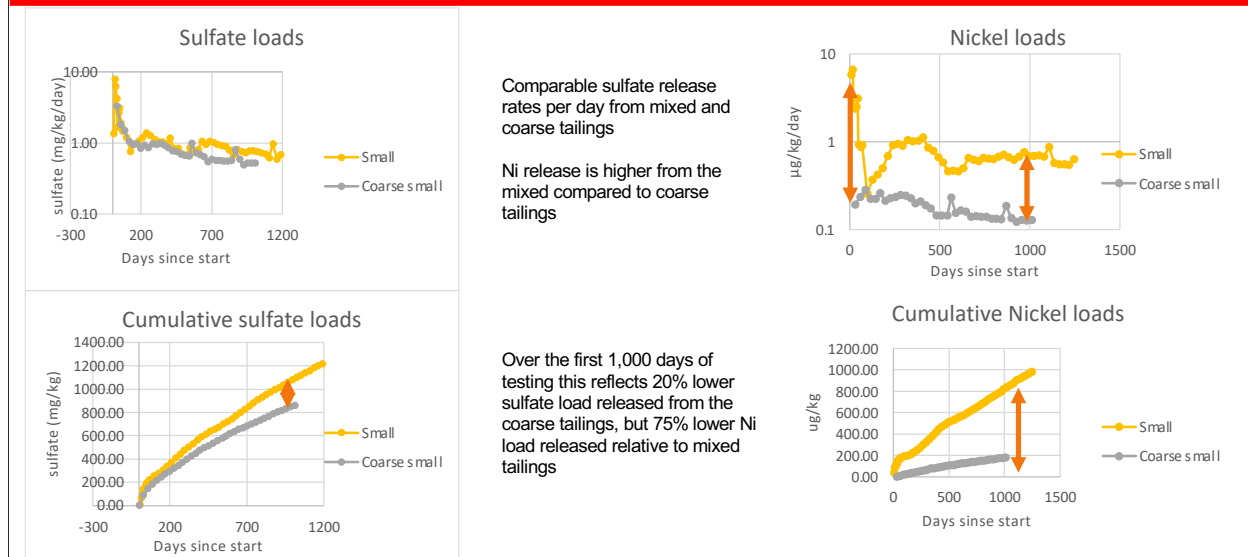
Geochemical analysis such as kinetic testing has shown that sufficient buffering from primary carbonates is available to produce near-neutral drainage from the low sulfur tailings. Risks associated with the primary mineralogy at the site relate to the relatively high mobility of Ni and Co along with sulfate in circum-neutral pH. Changes in pH are used to allow selectivity of the process towards the target metal in the different flotation steps.

The initial flotation is performed at high pH to recover copper, with the addition lime to increase the pH to ~11 or 12. The nickel recovery is conducted at lower pH by gradually lowering with the addition of acid for the nickel flotation. Thereafter, the scavenging flotation step separates the sulfides to produce the lower risk Tailings A, and the high sulfide Tailings B, although Ni remains highlight mobile in both.

Cumulative grain size distribution and liberation

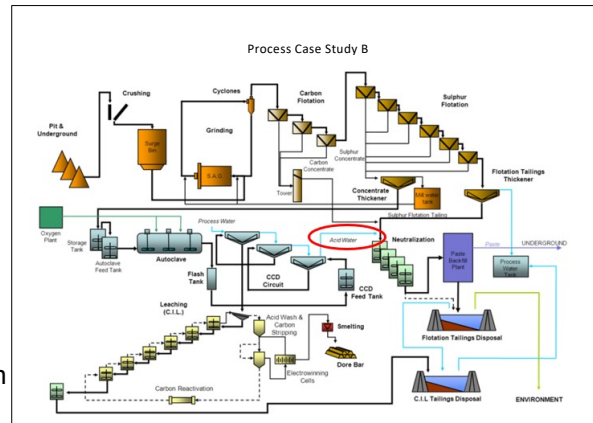


PSD effect on S and Ni release from tailings, investigating difference between beach and pond tailings



Case Study B: Overview

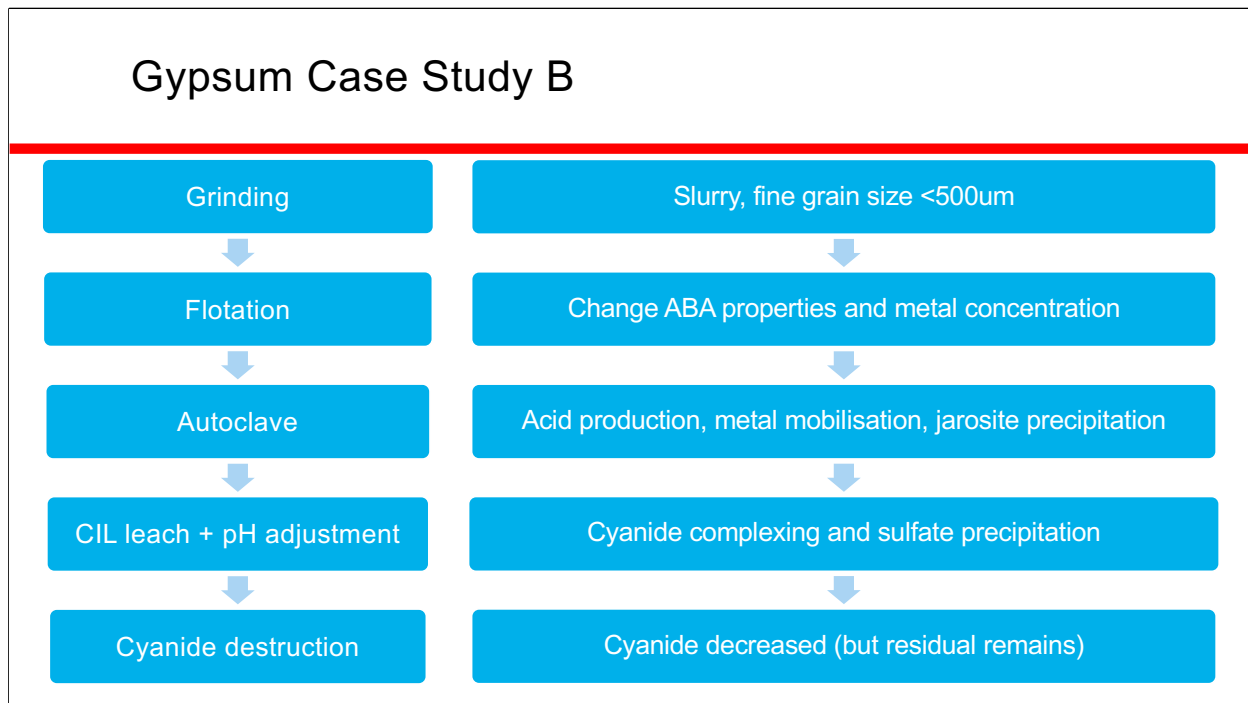
- Gold mainly bound inside As and sulfides
- Flotation to concentrate the gold (and sulfides) followed by pressure oxidation to destroy sulfides and carbon in leach (CIL) cyanide extraction to recover the gold.
- Results in two tailings products, a low sulfur tailings from flotation and a low sulfide tailings from the CIL
- Sufficient buffering from primary carbonates available to produce near-neutral drainage from the low sulfur flotation tailings, but releases Mg and sulfate
- AMD risks associated with CIL tailings is mobile arsenic associated with sulfates and high pH



Notes: Case study B is a gold mine in a greenstone belt with significant carbonates present in the host mineralogy.

The ore is floated to concentrate the gold followed by pressure oxidation to destroy sulfides and carbon in leach cyanide extraction to recover the gold. This results in two tailings products that are: a low sulfur tailings from flotation; and a low sulfide tailings from the CIL.

Kinetic testing indicates that sufficient buffering from primary carbonates is available to produce near-neutral drainage from the low sulfur flotation tailings. AMD risks associated with this ore relate to the relatively high mobile arsenic associated with sulfate in the CIL tails. Sulfides are oxidised during pressure oxidation step giving rise to low pH process water before lime dosing to increase the pH to over 9 to maintain cyanide in solution required for the gold extraction steps. However, this configuration also gives rise to significant gypsum formation in the tailings and contributes to arsenic mobility.

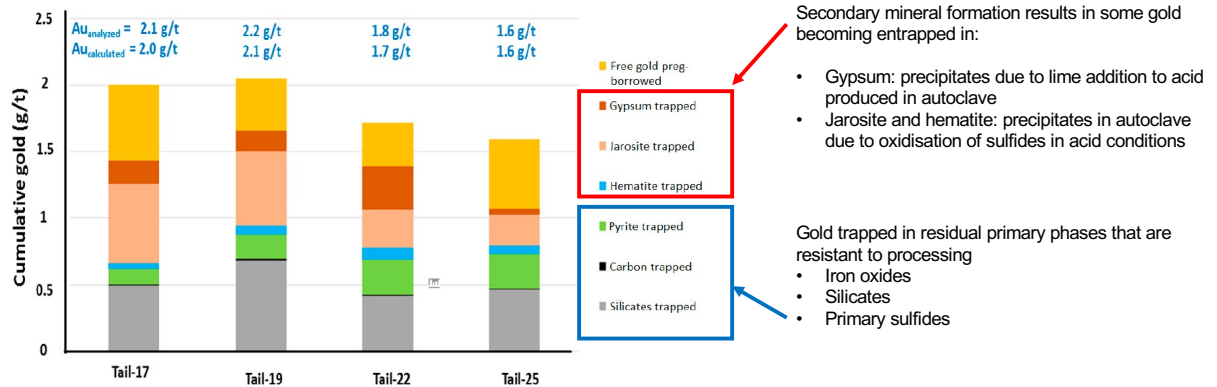


Notes: The process flow chart of the gold ore following these main steps is shown in the figure on the right and shows the two products: the neutralised tailings, and the CIL tailings. These two materials have differing mineral profiles and resulting challenges.

The neutralised tailings are produced after the initial carbon and sulfur flotation and therefore contain low sulfide sulfur, but high carbonates, such as dolomite. The neutralised tailings also contain approximately 2% sulfur, which equates to ~10% gypsum content; however, gypsum is not present in the primary rock, and is instead created during the processing. It is interpreted that in the adding the acidic process water from the sulfur concentrate pressure oxidation to the sulfur flotation tailings, adds sulfate ions to the otherwise relative sulfur-free neutralised tailings. The acidity dissolves some of the carbonates within these tailings, neutralising the acid, and releasing Magnesium cations in solution. As the pH is increased with the aid of the neutralisation step, the Magnesium and Sulfate react to form epsomite and gypsum.

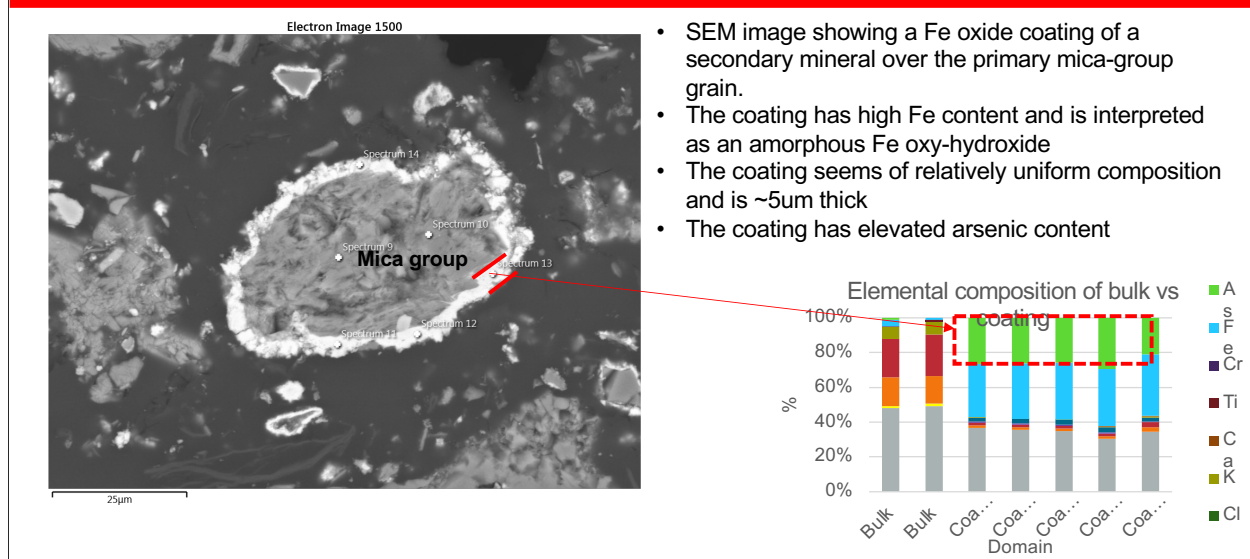
After the autoclave, the washed residue feeds into the CIL circuit. Here, cyanide is dosed as needed. Loaded carbon is used for stripping. A high pH is used through these stages to keep the cyanide dissolved. However, alkaline conditions leads to high arsenic mobility through the processing and into the final tailings. With a final pH of the CIL tailings at the spigot of ~8.5.

Secondary mineral precipitation considerations (recovery)



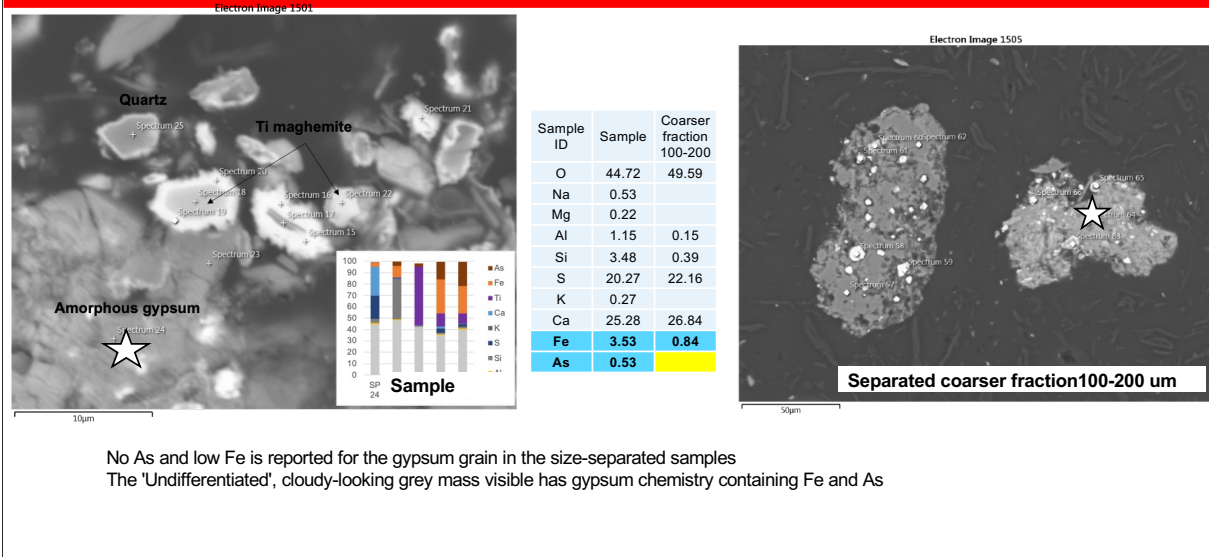
Edahbi et al 2019. CIL gold loss characterisation with oxidised leach tails (Minerals, 9)

Identifying secondary minerals



Notes: Here is another image showing a larger mica group grain with a well-developed coating around it. This coating appears more crystalline than the coatings on the previous slide. As before, the coating has high iron and arsenic content.

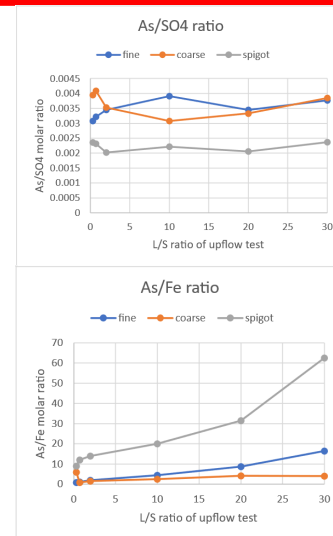
Amorphous and crystalline gypsum



Notes: Interestingly, gypsum could be seen in two forms – as grains, for example, in the separated coarser fraction of the sample, and as amorphous material as in the figure on the left. Both phases contained similar amounts of calcium, sulfur and oxygen supporting the identification of the phase. Notably, however, the well-formed grain contained only ~one quarter of the iron that was associated with the amorphous calcium sulfate, and no detectable arsenic, while the amorphous mass contained arsenic at ~0.5%. These results further support the arsenic release mechanism observed in the upflow being related to sulfate release, which is interpreted as resulting from the dissolution of the relatively abundant amorphous calcium sulfate phases such as the one in the left figure.

Arsenic Mobility

- As relatively low, highly mobile in alkaline conditions - the addition of lime in the CIL processing adds Ca ions into the process, which combine with sulfate ions to form As-containing gypsum
- Controlling cyanide in the process (detox) requires high pH – cyanide management designed to meeting compliance (cyanide code and regulations), not connected to ARDML consideration
- As levels correlate to sulfate levels - amount of gypsum created in the tailings and its solubility means that Arsenic trapped within this secondary mineral
- Elevated pH and presence of arsenic trapped in gypsum means relatively mobile source of arsenic in final tailings



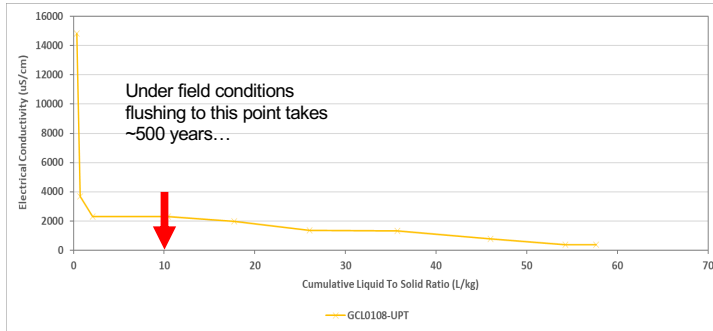
Notes: Arsenic mobility is a compliance parameter of concern.

The addition of lime in the CIL processing steps contributes Calcium ions into the process, which combine with sulfate ions to form Arsenic-containing gypsum. While the percentage of Arsenic within gypsum is relatively low compared to Arsenic within metal oxides or metal sulfates, such as jarosite, the amount of gypsum created in the tailings and its solubility mean that As trapped within this secondary mineral is released at problematic concentrations.

Concentration of arsenic in testing correlated to that of sulfate, and not that of iron. This gypsum source will continue to leach arsenic at elevated concentrations as long as the gypsum source persists. Given the low net percolation rates expected in field conditions, this process will likely dominate seepage geochemical composition over the long term. The elevated arsenic concentration observed in weathered tailings with acidic decant quality is likely due to desorption of arsenic from sorption sites, rather than release of arsenic from primary sulfides, or acid-driven dissolution of the As-jarosite in the sample. In high pH solutions arsenic is also mobile, which reflects the potential risks of higher metal release resulting from high pH conditions, such as in the CIL tanks where pH of >9 is required for safe manipulation of cyanide.

Chasing cyanide in the process with high pH offers a downstream challenge in controlling arsenic concentrations in percolation-generated leachate. High pH is required to keep arsenic in solution in high concentrations and becomes trapped in other minerals that form.

Duration of flushing of secondary sulfates



L/S ratio of >50 required to remove gypsum.....effective infinity timescale

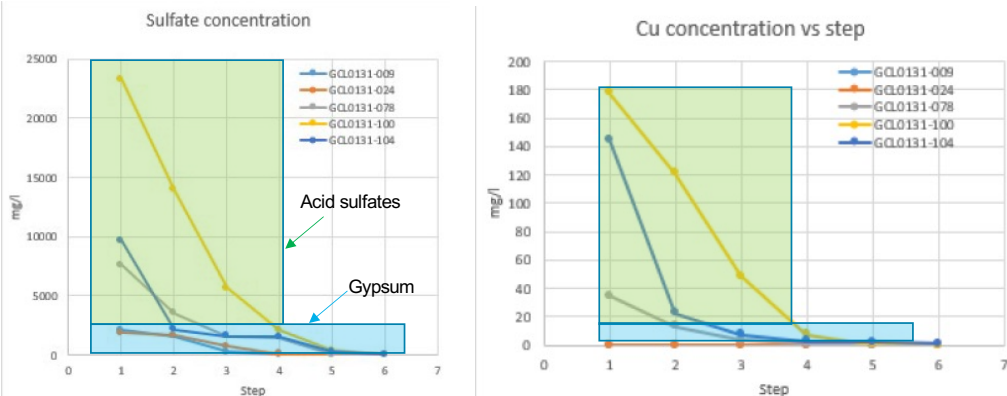
Consideration of not creating gypsum in the first place e.g. use sodium hydroxide instead of calcium hydroxide

Time [years] required to wash out process water and salts from pore water

Thickness [m]	Net Percolation [mm]			
	500	300	150	50
<i>One pore volume (replaces initial decant)</i>				
5	4	7	13	40
10	8	13	27	80
20	16	27	53	160
<i>Ten pore volumes</i>				
5	40	67	133	400
10	80	133	267	800
20	160	267	533	1600
<i>Twenty pore volumes</i>				
5	80	133	267	800
10	160	267	533	1600
20	320	533	1067	3200

Assume 20m thick tailings profile and 300mm/yr NP

Case study C: copper leaching linked to unstable acid sulfates (oxidation of sulfides)

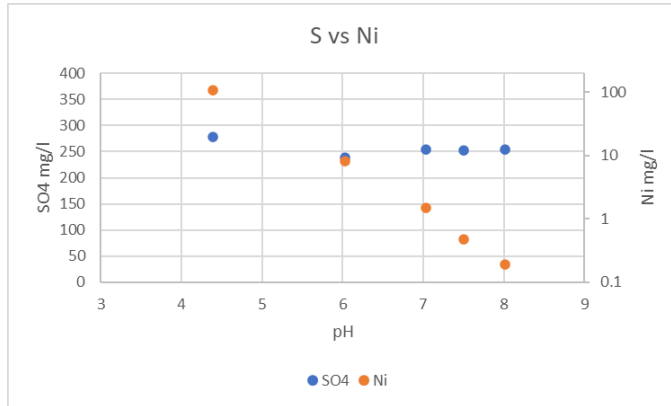


- In this case absence of suitable carbonate buffering minerals means that mobile acid salts are main source of metal release upon oxidation of residual sulfides
- Gypsum less significant source of metals

Notes: Gypsum and epsomite are both sulfate minerals that can form in tailings due to processing, and as we indicated on the previous slide, the neutralant used will influence mineral speciation and quantity. The leach behaviour of different sulfates differs, however. Epsomite (magnesium sulfate) is more soluble than gypsum and releases higher sulfate concentrations in the leachate compared to calcium sulfate. In this plot of upflow test results shown on the left, the dissolution of epsomite is evidenced by the high magnesium concentration alongside high sulfate. The decrease in Mg concentration indicates the switch to gypsum dissolution/precipitation controlled system. Gypsum is often the dominant sulfate and present in high quantities, controlling leach quality over a long period of time (a liquid to solid ratio of over 17 can reflect time periods into hundreds of years depending on net percolation).

We can also see that actually, the concentrations of metals (here copper) follow closely the concentration of sulfate, indicating a linked release mechanism. Since the release of sulfate is interpreted as relating to the dissolution of secondary sulfate-bearing phases, it is therefore inferred that the copper is also released from these secondary minerals.

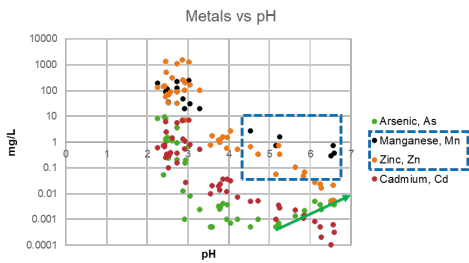
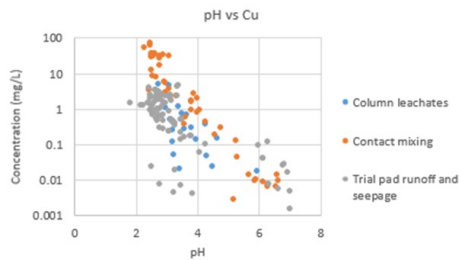
Case study D: pH dependant nickel leaching linked to de-sorption from iron hydroxides



- Nickel release related to pH not sulfate during leach tests, indicates that nickel source is semi stable fraction likely within hydroxide coatings.
- Nickel release will occur irrespective of sulfide oxidation if pH drops after material placement
- Note that very acid pH not required, @ pH 4.5 >100mg/l Ni
- Opportunity for metal recovery? Very weak acid leach needed only to recover mobile nickel

pH dependant leach test carried out on fresh tailings sample obtained direct from process plant at nickel mine

Case study E: Implications for future tailings management



Co-disposal of waste rock and tailings

- Filtered tailings from CIL process
- Tailings from process pH=8 and low metal mobility, gypsum + iron oxides from processing present + residual cyanide
- pH dependant leach of tailings indicates metals released when pH drops below 5 (i.e. semi stable)
- Reactive waste rock variable acidity, some acid from exposure during mining
- When mixed together metal release is pH dependant (log) indicating that semi stable metals in tailings are mobilised when mixture is moderately acidic

Production of semi stable minerals during processing thus significant source of ARDML risk when co-disposing waste rock and tailings

Conclusion

- Recovery drives the process design, management of tailings treated as downstream activity leading to practice of “management of what is produced” rather than informing the process design to produce “what is required” for optimal tailings risk management. Why otherwise have slurry tailings been the dominant tailings product?
- With respect to specification of grinding circuits, consideration of the cost benefit of grind size with respect to geochemical and geotechnical stability of tailings as well as recovery is required
- Quick lime most commonly used modifier, relatedly cheap, but downstream risk from tails may not fully be considered. The precipitation of gypsum which produces a long term source of sulfate and co-precipitated metals release.
- Consideration of the quasi stability of metal phases and the ease of the de-sorption process related to changes in pH post deposition, especially considering filtered tailings and co-disposal options

When assessing the establishment or changes to the recovery processes the opportunity should be taken to consider the recovery values against the potential AMD and geotechnical risk from the tails and the opportunities to reduce closure risk measures associated with the management of the geochemical risks of tails through operations, active closure and passive closure phases.

Tailings design and risk management process starts with the process flow sheet

Notes: The processing of ore and tailings management are interdependent, however, are generally managed separately. This review of the ore processing with consideration of the effect it has on the tailings has allowed the identification of some key steps in the processing where decisions made during process flow design can significantly influence the AMD risk from the tailings.

Optimisation opportunities exist as part of process flow design to reduce AMD risks for example a small increase in grind size to reduce metal release potential, the prevention of gypsum formation to reduce long term sulfate release and consideration of gypsum formation and dissolution on metal leaching risks, consideration of pH adjustment steps in the process and impact on metal mobility, and the consideration of host rock carbonate mineralogy when assessing acid neutralising steps.

When assessing the establishment or changes to the recovery processes the opportunity should be taken to consider the recovery values against the potential AMD risk from the tails and the opportunities to reduce the active and passive closure measures associated with the management of the geochemical risks of tails through operations, active closure and passive closure phases.



Thank you

www.memconsultants.co.uk

Mine Environment Management Ltd