Paste for In-Pit Tailings Disposal Applications

Ibrahim Karajeh
Golder Associates Ltd., Mississauga, Ontario, Canada

ABSTRACT

Many mines start as an open pit operation and advance into underground developments. In some cases, paste is selected as the backfill method of choice. For these operations the potential to place tailings in the existing inactive open pit can be beneficial from an environmental and cost perspective. The operation can delay or eliminate the need to permit a new tailings storage facility. One of the key challenges with in-pit deposition in general is the management of water. A highly dewatered tailings such as paste can be the solution, and to those operations that have a paste backfill plant, the advantages are apparent. This paper discusses the engineering considerations for an in-pit tailings disposal design with a particular focus on the advantages of delivering a paste consistency material.

INTRODUCTION

Paste for underground backfill, surface disposal, or both in some cases, is gaining more acceptance among mining operations over the past three decades. Perceived operational risks and questioned economic feasibility are being reduced as a result of many successes witnessed among paste technology adopters. Yet, and despite being economically feasible, the best paste facility intended strictly for underground backfill will still fall significantly short of full utilization. These utilization values typically fall within the 40-60% window depending on the site specific mining method and hence availability of stopes to fill. The dual use of paste for underground backfill and surface (or in-pit) disposal provides the opportunity to maximize the utilization of the paste production facility and hence improving the return on the investment in paste technology, providing additional incentive for decision makers sitting on the fence between investment in paste and other backfill options.

Water is an inherited ingredient in mine tailings. Most mineral processing technologies involve pulping of the solids in liquids as the most effective method to handle and transport these solids. Analysis of the incidences that took place in the 1960's shows failure to manage water as a major contributor to tailings dam failures. These failures claimed hundreds of lives, caused lots of personnel injuries, billions of dollars of property damage and significant damage to the mining industry's public image. Failures of conventional tailings storage facilities contributed to the mounting pressure to reduce the waste environmental footprint created on the planet by mining operations. In light of recent tailings dam failure disasters the mining community is realizing the importance of finding alternatives to the conventional tailings management methods. Containment of material that contains two thirds of its weight as water by dams is understandably risky. The industry is looking into alternatives for how the tailings are placed and where the tailings are placed. Paste, a non-segregating mixture of solids and water, that has practically no water bleed when left idle, and most importantly that possesses a yield stress offers an alternative that needs to be considered. Deployment of cemented paste underground as backfill eases the pressure on conventional tailings management facilities as they have to handle less volume. After thickening and dewatering of tailings, deposition in the form of paste improves the efficiency and effectiveness of conventional tailings impoundments as paste stacks geometrically better in addition to being volumetrically more compact. And, with almost all residual water left in the tailings retained in the paste the concern about water is significantly reduced. The trajectory of this trend is dry stacking which has been gaining popularity despite the relatively high operating costs when compared to conventional slurry and thickened tailings methods. It is worth mentioning that to many operations the benefits of dry stacking over paste outweigh the marginally higher operating cost. These benefits include the stability of the deposition and the ability to transport the tailings via trucks or belt conveyors, a method familiar to mining operations compared to the challenging paste pumping.

Deposition of paste into exhausted open pits offers additional advantages over surface disposal. There are challenges and potential draw backs associated with this approach. This paper discusses these challenges along with the advantages associated with use of paste technology for deposition of tailings into exhausted open pits.

AN OPEN PIT VERSUS A SURFACE TAILINGS STORAGE FACILITY (TSF)

Physical stability is an obvious necessity for a tailings management method to be considered sustainable. The rating of each failure risk is a function of two components, the probability of a compromised physical stability that will eventually lead to a failure in a specific mode and the consequences of that occurrence should the risk materialize. Historically, TSF failures were attributed to dam over topping due to improper operation or under estimation of precipitation and flood flows, embankment failure due to uncontrolled seepage or liquefaction of fine grained or granular materials under earthwork loading conditions, or foundation failure. Open pit walls are intrinsically more physically stable when compared to TSF dams. The risk is significantly lowered due to an order of magnitude less probability of the physical stability being compromised. Consequences of surface TSF failures are usually catastrophic as the content of these containments runs for kilometers and in many cases encounters people in the way.

In pit disposal offers other advantages over disposal in a TSF located on surface. These advantages include friendlier aesthetics, especially after closure, and better control of erosion from wind and runoff.

Potential contamination of aquafers and the proximity of the open pit to active underground workings are matters that need to be carefully studied. Risks associated with these matters require detailed assessment with mitigation measures put in place prior to decision to pursue in pit disposal. Discussion on these challenges and ways to mitigate the risks associated with them is included in subsequent sections of this paper.

DEPOSITION IN THE FORM OF PASTE VERSUS SLURRY

A Description of Paste

Despite the fact paste has been around for several decades now it is still difficult to find agreement among practitioners about a single and comprehensive definition of ‘paste’. However, there is general acceptance of a few characteristics that when exhibited by a mixture of solids and water it can be described as paste. These characteristics include:

- Exhibits minimal to no water bleed when left idle.
- Has a slump of 6 to 10 inches.
- Non-segregating and hence not requiring movement at a minimum velocity to avoid settling of solids.

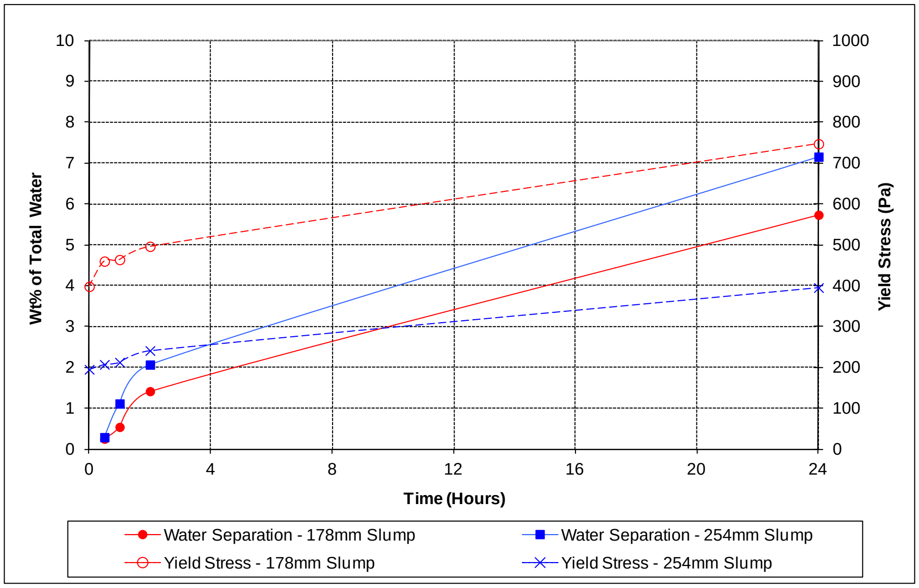

Figure 1. Water separation and yield stress versus time left idle for 7 inch and 10 inch slump zinc tailings paste

Figure 2. Mixture of solids and water at different densities forming no slump (left), 10 inch slump (middle) and 7 inch slump (right)

Every item in the above list plays an important role in determination of design and operational aspects of a paste system like for example the method and extent of tailings dewatering, paste delivery system attributes and the performance envelop of the paste fill in terms of geometrical & dimensional limitations, strength and curing time. For example, in a case where cemented paste is used for backfill a lower water content improves binder economics on one hand but demands higher capital and operating costs to prepare and deliver 'thicker' paste. Another example is water bleed performance and the increase of yield stress with time. These attributes can be of paramount importance if paste is considered for a surface disposal operation.

Paste Characteristics Relevant to in Pit Disposal

Slurry is the form of tailings that mining operations are familiar with, used to and comfortable with for decades. Capital cost is kept at relatively low levels through investment in conventional thickeners, centrifugal pumps, piping and tailings storage facilities. Operating cost is also limited to pumping power and maintenance. Methods and technologies used are relatively straight forward and well established. The drawback is the large amount of water contained in the tailings slurry which will eventually get ponded on top of the tailings. This water is a major contributor to a higher risk consequence given the fact water is what transports the tailings for long distances in the event of failure. Tailings management methods based on slurry are usually designed with provisions to manage the water. However, these provisions have limitations as history has shown. The risk of flow of tailings placed in open pits into adjacent underground workings exceeds risk tolerance at most sites and is usually treated with avoidance of the risk. The risk is directly tied in terms of probability and consequences to the amount of water contained in these tailings.

Paste is made by dewatering the tailings slurry. Slurry normally has a density that ranges between 25 and 35% solids by weight although some sites pump tailings at a density as low as 15%. Paste density is usually in the 70% to 74% range for a typical gold or base metal tailings. Figure 5 below is a simple chart showing volume of water per unit weight of tailings dry solids. A reduction of water volume by an order of 6 – 7 times is achievable by dewatering tailings slurry to paste consistency.

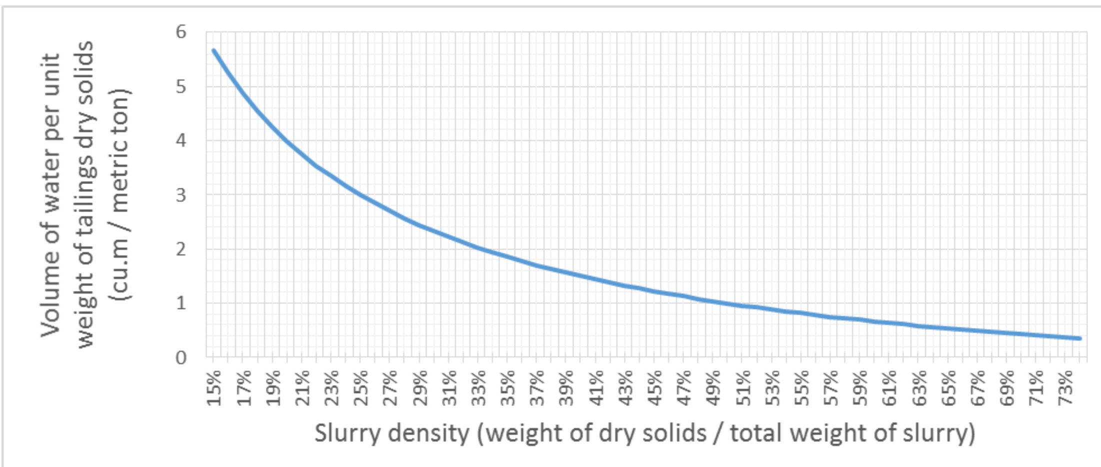

Figure 5. Volume of water contained in tailings slurry versus tailings slurry density. Slurry density is expressed as percentage of dry solids weight per unit of total slurry weight.

In addition to the obvious advantage of water conservation which can be a driver on its own in some geographic locations, the reduction of the overall tailings 'mixture' volume significantly increases the volumetric efficiency for tailings placement. More importantly, paste takes a large amount of water out of the equation. Deposition in thin layers allowing each layer to dry out and desiccate before a subsequent layer is deposited on top improves the stability.

Other Benefits Associated with Paste in Open Pit Disposal

The following are among the additional benefits of in-pit disposal of mine tailings in the form of paste:

- Minimize foot print: open pits are considered lands already disturbed by mining activities. Permitting the construction or expansion of tailings storage facilities will involve disturbing more land. Regulators and environmental agencies will in many instances prefer the deployment of mine waste into underground in the form of backfill or in mined out open pits over deployment of the waste in the form of slurry within impoundments built on surface.
- Other indirect ways of minimizing impact on the environment is the reduction of water volumes being moved around which results in less water lost through seepage and evaporation. This translates into less fresh water being withdrawn from the environment.

- Designing for closure: Proper mine planning takes in consideration the closure part of the life cycle in order to assure incorporation of the closure plan requirements in construction and operation of the mine. Open pits are required to be closed by backfilling or flooding to the extent practicable to prevent unauthorized access and to protect public safety. Alternatively, fencing is required in cases where backfilling or flooding is not possible. Filling open pits with paste that is capable of gaining sufficient strength satisfies these closure requirements. This enables landscaping and revegetation of the open pit foot print which is a form of closure more in line with the return of the site to nature in a self-sustaining ecosystem that bears more resemblance to the original natural status prior to the mining activities.
- Paste plant life cycle economics: mining operations that invested in paste plants for underground backfill can capitalize on their investment and improve the overall life cycle economics by increasing the utilization of the paste plant. Modern paste plants are designed and constructed to the same standards metallurgical plants are built to. They are built to last for lives approaching or exceeding 15 years. They are automated and equipped with safety and operational features similar to the ones available to a typical mill. They are built with generous head rooms, space clearances and accessibility allowances that warrant proper maintainability and high level of reliability. Their availability can be as high 98%. Although each site has its own specific conditions and cost for each paste plant depends on the paste recipe and nature of the tailings handled but a typical paste plant with a capacity between 4,000 to 8,000 dry metric tons per day (tpd) costs a capital in the range of US$50 million. When used for cemented backfill, the annual operating cost is as detailed in the table below. Utilization is assumed to be 60%.

Table 1. Annual operating cost for paste backfill plant

Item	**Annual Operating Cost (US$000)**	
	4,000 tpd Plant	**8,000 tpd Plant**
Binder	5,800	11,600
Electrical Power	910	1,500
Flocculent	110	220
Spares, Lubricants & Other Maintenance Consumables	80	130
Total Variable Cost	**6,900**	**13,450**
Fixed Cost	**3,100**	**3,400**
Total Cost	**10,000**	**16,850**

- The fixed cost, slightly over US$3 million in the example, represents supervision and operation personnel, facility building maintenance and operating costs and share of overheads. This cost is incurred regardless of the plant utilization level. Benefit-cost analysis run to investigate the feasibility of an investment in a dual purpose paste system where the paste production continues when no backfill is being placed underground can consider this fixed cost to be in favor of the decision to invest.
- Reduced, and delayed, capital investment in tailings storage facility: For a typical paste plant with an instantaneous nameplate capacity between 4,000 and 8,000 dry metric tons per day the marginal cost of making uncemented paste out of one metric ton of tailings (dry basis) is around US$1.3 in the case of 4,000 tpd and US$1 in the case of 8,000 tpd. Assuming an availability of

97% for the combination of the paste plant and the mill. When such a plant is serving backfill only 60% of the time the balance annual capacity available during the remaining 37% of the time is 540,000 to 1,000,000 worth of dry metric tons of tailings. Dewatering of tailings slurry into paste consistency costs US$700,000 to $1 million. If these tailings are normally sent to conventional slurry TSF and the paste made from them can be placed in an open pit then that defers the investment in TSF dam raise or construction of a new TSF. This investment in making paste is likely feasible. The additional US$0.7 to $1 million can easily offset dam maintenance and construction cost capital recovery.

- Opportunity for co-disposal: mine sites that face challenge with managing potentially acid generating waste rock can benefit from disposal of paste into the open pit if a co-disposal concept is adopted. Paste can encapsulate waste rock and hence prevent oxidation. This reduces the cost for management and closure of acid generating waste rock facilities.

CHALLENGES ASSOCIATED WITH PASTE IN PIT DISPOSAL

Potential Contamination of Water

Due to their locations, shapes and depths open pits are practically sinks where water flows into from either surface or ground. Part of that water either evaporates or continues to flow to other underground voids and cavities whether natural or manmade. The remaining balance of water ponds in the open pit and requires to be pumped out if access to the open pit is required. In normal circumstances the mine water management plan involves procedures to monitor, test and manage water that may need to be pumped out of the open pit. However, when paste is being placed inside the open pit water may get in contact with the paste and water chemistry may get altered in a way that requires changing the water management plan. In addition to the nature of the tailings the extent of this risk is a function of the site specific climatic, topographic and hydrogeological conditions. There are several ways to counter this challenge that includes:

- Additives: including a binder like cement in the paste in order to prevent metals and other contaminants from leaching to water that gets in contact with paste.
- Selective placement of engineered products: where different specification materials are placed in different locations of the pit in order to provide a specific function in lieu of bulk deposition of homogeneous paste. For example a method know as Pervious Surround Method is used in the uranium mines. A layer of a highly permeable material is installed around the tailings to allow free groundwater circulation around the tailings. Paste is highly impermeable and hence nearly no exchange of contaminants between tailings and groundwater takes place. Berms and special site grading can minimize the amount of surface water that flows into open pit.
- Adjusting the water management plan: by including additional measures for water monitoring, testing, pumping and treatment. This may have capital and operating cost impacts but may still fall within the overall economic feasibility.

Timing

Based on economical merits alone it is unlikely that an investment in a paste operation be justified without the high returns from an underground backfill process. In most cases the transition to underground mining overlaps with the tail end of open pit operation. Thus, even if a paste plant is commissioned by the time underground backfill is required it is unlikely that deposition into open pit is an available option for some period of time. This makes the continuation of pumping tailings to surface tailings storage facilities a necessity until the open pit is fully decommissioned and all necessary measures to assure safe deposition of paste into the open pit are taken.

Risk to Underground

Liquefaction and sudden rush into underground workings is a risk that poses a deterrent to putting tailings in an open pit where an active underground mining operation is in proximity. The 1970 Mufulira Mine disaster in Zambia which claimed the lives of 89 miners happened as a result of one million tons of tailings flowing from the bottom of a surface tailings impoundment through a sink hole that formed and extended all the way down to underground workings. Storage of tailings in an open pit close to active underground workings bears a resemblance to the Mufulira case. Risk can be mitigated by:

- Reducing the probability of occurrence by mounting structural barriers that prevent entry of material into underground working in the case of liquefaction. Barricades can be built to seal adits and other openings where underground workings intersect open pit walls. This requires proper mapping of underground workings which can be a challenge in sites abandoned for long times and being reactivated. A plug can also be poured at the bottom of the pit where interface between open pit and underground across the crown pillar and the continuation of the ore zone is more likely to be located.
- Reducing the probability of occurrence by placement of paste in thin layers and allowing it to dry out and desiccate. Hence, reducing the likelihood of the paste liquefaction. Advantage of thicker paste is an obvious advantage here given the system is designed to enable delivery of the paste to all deposition spigots.
- Adding binder to the paste reduces the likelihood of liquefaction as binder hydration consumes the water dispersed in the paste solids. It also reduces the consequences should one layer or body of the paste placed in pit undergoes liquefaction as the cemented paste around, above or below the liquefied portion hardens and hence limits the extent the liquefied portion travels.

Sterilization of Potential Ore Bodies

Backfilling of open pits makes some ore bodies inaccessible for future recovery. Although this is more of an issue when tailings are placed in the form of slurry. Paste backfill that gains strength over time may offer a solution to this matter.

RECOMMENDATIONS FOR OPTIMAL ECONOMICS

Mining operations planning the transition from open pit to underground mining are encouraged to consider the following:

Planning

- Adopt a versatile, dynamic and long term plan built on modelling of all possible scenarios taking in consideration potential changes in stakeholders' requirements. Aim at multiple use and maximizing utilization of assets.
- Engineered investment: despite the lower unit cost benefits that investment in a high capacity operation offers, a phased approach or 'telescoped' investment may offer benefits that

outweigh economies of scale benefits. These include mitigation of risk, progressive development where one phase experience contributes to the refinement of the subsequent phase and enabling the investment to take off when financing is limited. Pilot testing is an extreme version of the telescoping concept. It can also be used as a 'proof of concept' to demonstrate an option or a combination of options and obtain the support of stakeholders.

- Record updates: todays technological developments leave very little to guessing and estimation. Drones can be flown into locations normally deemed unsafe for human access to collect data and perform scanning for the purposes of mapping historical underground workings or open pits. Ground penetrating radar technology can be used to reveal details not available to the naked eye.

Engineered Deposition

Consider selective placement of different specification material in different locations depending on the function required from the material. Deposition of a highly permeable layer around the tailings to allow ground water to flow freely around the tailings rather than through them as discussed earlier is one example. Placement of highly cemented paste in specific locations to have a structural function is another example. A third example is capitalization on the paste plant's dewatering capacity and dry stacking of filter cake in selective parts of the mined out open pit. The pictures below show a successful application of this concept.

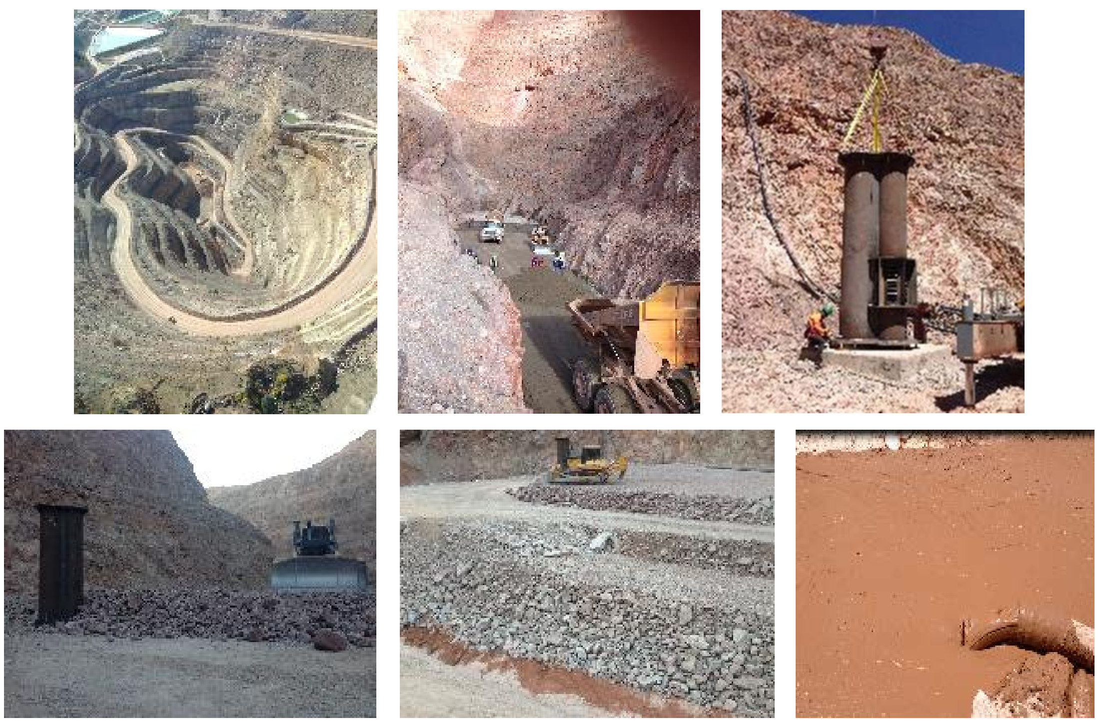

Figure 6. Progressive deployment of fill into mined out open pit. Upper left: Pinos Altos Mine Oberon de Weber open pit prior to start of fill. Upper middle: Placement of roller compacted concrete layer. Upper right: Installation of the 1st section of pit dewatering pump well. Lower left: Placement of a rock fill drainage layer. Lower middle: Placement of a filter layer of rock fill. Lower right: Cemented paste pouring. Courtesy of Agnico Eagle Mines Limited.

Figure 7. Progressive deployment of fill into mined out open pit - continued. Upper left and middle: Paste pouring against hanging wall fault to prevent water ingress. Upper right and lower left: Cemented paste allowed to dry. Lower middle: Additional layers of cemented paste poured and allowed to dry. Lower right: Stacking of filtered tailings. Courtesy of Agnico Eagle Mines Limited.

CONCLUSION

Today's mining industry is facing significant head winds with declining commodity prices, less investors' appetite towards resource sector, challenges with financing, and high public expectations for environmental, health, safety and social stewardship. More than ever, there is a need to innovate in order to warrant sustainability. Not all innovations require a technological leap. In many cases creating synergies and maximizing utilization of assets can be as effective as innovation that is built on major technological developments.

The investment a mining operation makes in paste backfill can pay dividends given it suits the mining method selection and paste plant sizing and design falls within the optimal envelope. Innovative utilization of the paste plant assets could accelerate pay back on the investment. Making paste involves several separation and mixing processes. With an incremental increase on capital paste plants can be configured to produce multiple products or multiple specifications of multiple trains. They can also be configured to produce in multiple modes. The final outcome is a facility with more than one potential product, utilization and mode of operation. This includes products like flocculated and thickened tailings, filter cake, cemented and uncemented paste with varying consistencies and combinations of these products. Deposition methods may include underground backfill, surface disposal in tailings storage facilities, dry stacking on surface, in pit disposal, co-disposal with other streams like waste rock and combinations of these methods. Coupling the need to close a mined out open pit with the need to manage mine waste streams is nothing short of innovative. Utilizing paste production capacity and engineering a selective deposition scheme is a multiplier that emphasizes the rewards reaped from applying this tailings in open pit concept.

Decisions to invest in paste are usually driven by the benefits sought from enabling the continuation of underground mining operations, improving the overall stope mining and backfilling cycle, lower binder cost and better underground environment compared to other backfilling methods. Let us consider a typical paste plant with a capacity between 4,000 to 8,000 dry metric tons per day again. Annual total operating cost is typically in the range of US$10 to $17 million (4,000 tpd and 8,000 respectively). Assuming an annual escalation rate of 3.5% and an internal rate of return (IRR) equivalent to 20%, a paste operation has to generate annual benefits equivalent to approximately US$22.7 to $30.3 million (4,000 tpd and 8,000 respectively) in order to offset the operating costs and recover a capital investment of US$50 million over 15 years. With only 60% utilization this translates to a sought benefit of US$17.4 to $26 per metric ton of dry material placed underground in the form of cemented paste backfill to break even. The $17.4 corresponds to the 8,000 tons per day and $26 corresponds to 4,000 tons per day. The fact that paste plants continue to be built and operations' retrospect supports feasible investment that consistently pays back suggest the notion these returns are common place. If a plant of a similar range of capacity is utilized at 97% rate for the sole purpose of making uncemented paste for surface or in pit disposal then a sought benefit of US$6.3 to $11.7 per metric ton of dry material placed is required to justify the investment. Thus, evaluating strictly from an economical point of view backfill is the primary driver behind the investment in paste operations. Economies of scale play a factor in cases where capacities are significantly higher than 8,000 tons per day. Other considerations like environmental and public safety can have significant benefits. Quantification of these benefits is not included in the above analysis.

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