

**Paste Backfill Geochemistry –
Environmental Effects of
Leaching and Weathering
MEND Report 10.2**

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Environmental Effects of Leaching
and Weathering**

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EXECUTIVE SUMMARY

The influence of paste backfill on operational and long-term mine and ground water quality has been identified as one of the priorities of the MEND Program. This report provides a brief summary pertaining to current practices in the geochemical characterization of both cemented and uncemented paste backfill, and methods used to predict environmental impacts to surface and ground water quality associated with the application of paste backfill in underground applications. Data was collected via a literature review, and a survey of mines known to use paste backfill.

The findings indicate that the amount of available information and research on the influence of underground paste backfill on mine water quality is typical of a relatively new field. To date, research by the community at large has focused on the structural characteristics of paste in terms of meeting the required backfill strength using the most economic amount and mix of binder materials. In light of the belief that the chemical reactivity of tailings and the volume of leachate generated are reduced by thickening, and by the addition of alkaline additives such as cement, little information on the influence of paste backfill on mine water quality appears to have been developed.

Exceptions have been where:

- the mineralogy and reactivity are extreme, with potential effects on paste strength;
- a portion of the paste is being deposited on surface (with potential surface water impacts); and,
- concern regarding potential ground water contamination from underground waste disposal in the United States led to initiation of the Underground Injection Control (UIC) Program that incidentally includes placement of mine waste backfill in underground mines under its legislation (Levens et al., 1996).

Recognition of the fact that any backfill has the potential to generate contaminant plumes in the long term, and potentially influence ground and/or surface water appears to have increased the site-specific evaluation of paste characteristics of newly proposed mines in recent years.

Despite the lack of extensive detailed study, the use of paste backfill in underground environments has been generally considered beneficial to reduce overall environmental impacts associated with mining, due to:

1. Reduction in the volume of tailings requiring surface disposal, thereby reducing surface impacts through footprint reduction;

2. Use of the full tailings stream in the backfill, rather than the coarse fraction used in more conventional sand fill, thereby reducing the need to handle and dispose of a separate slimes stream;
3. Reduction in the potential for tailings to oxidize or leach due to the nature of thickened tailings placed as underground backfill because of:
 - Less free water, which reduces leachate generation;
 - Less available oxygen as a result of the higher degree of saturation;
 - Preferential flow of ground water around backfill, rather than through it due to the lower hydraulic conductivity of the paste backfill;
 - The addition of cement that provides extra neutralization potential (NP) and decreases effective porosity; and,
 - The potential for flooding at closure which reduces sulphide oxidation in long-term.

The general theories associated with paste backfill characteristics and geochemical reactivity appear sound, but there does not appear to be much field validation on the actual influence of key parameters. Lack of controlled conditions in active mine environments appears to significantly limit the ability to separately assess potential scale up issues. The field would benefit from research targeted at the specific components of paste theory (such as the separation of the influence of thickening and binder addition), examination of scale-up issues (preferably in the controlled environment of an isolated well characterized and instrumented backfilled stope), collection of detailed case studies, and additional monitoring of mine waters to assess the influence of paste backfill on mine water quality over time. The lack of detailed information currently available is of concern, and highlights the need to compile detailed site data and monitoring data for future assessment and validation of predictions currently being initiated. And as with any new field, establishing a standard base of terminology would be useful.

In the bigger picture, there may be a need to better define the potential importance of this issue, such that priorities for studying this matter can be assessed. For example, are existing backfilled mines producing significant ground water contaminant plumes? Certainly sidehill mines that continue to drain from portals or other openings are known to be potential closure problems when not suitably mitigated (i.e. Britannia Mine in B.C., Canada; Summitville Mine in Colorado, U.S.). And there appears to be sufficient information to suggest that there might be potential impacts from backfilled mines where the wall rock and backfill are particularly reactive (i.e. Bernier and Li, 2003). However, a general survey of existing underground mines might put the significance of the issue in perspective.

RÉSUMÉ

L'influence du remblai en pâte sur la qualité opérationnelle et à long terme de l'eau d'exhaure et de l'eau souterraine est l'une des priorités du programme NEDEM. Ce rapport résume brièvement les pratiques qui sont actuellement en cours pour la caractérisation géochimique du remblai en pâte cimenté et non cimenté et les méthodes qui sont utilisées pour prévoir les répercussions sur la qualité de l'eau de surface et de l'eau souterraine, et sur la construction de remblais en pâte dans les mines souterraines. Les données ont été recueillies par le biais d'une revue de la littérature et d'une enquête auprès des mines utilisant le remblai en pâte.

La quantité d'information et de recherches disponibles quant à l'influence du remblai en pâte souterrain sur la qualité de l'eau d'exhaure est typique des domaines relativement nouveaux. À ce jour, la recherche menée par l'ensemble de la communauté a mis l'accent sur les caractéristiques structurales de la pâte qui donnent au remblai la résistance nécessaire tout en permettant d'utiliser la quantité et le mélange de liants les plus économiques. Il semble n'exister que peu d'information sur l'influence du remblai en pâte sur la qualité de l'eau d'exhaure, parce qu'on croit que la réactivité chimique des résidus et le volume du lixiviat produit sont réduits par un épaissement et par l'ajout de ciment ou d'autres additifs alcalins.

Ces situations font exception :

- la minéralogie et la réactivité sont extrêmes et pourraient éventuellement avoir des répercussions sur la résistance de la pâte;
- une portion de la pâte est déposée en surface, ce qui pourrait éventuellement avoir un impact sur l'eau de surface; et
- comme les États-Unis craignaient que la déposition souterraine des résidus ne contamine l'eau souterraine, ils ont créé l'Underground Injection Control (UIC) Program, qui comporte l'utilisation du remblais en résidus miniers dans des mines souterraines en vertu de sa législation (Levens et al., 1996).

La reconnaissance du fait que tout remblai peut éventuellement créer à long terme des panaches de contamination et avoir une influence sur l'eau souterraine et (ou) de surface semble avoir accru l'évaluation spécifique au site des caractéristiques de la pâte dans le cas des mines nouvellement proposées au cours des dernières années.

Malgré l'absence d'une étude détaillée complète, l'utilisation du remblai en pâte dans les environnements souterrains est généralement vue comme étant bénéfique pour réduire dans leur ensemble les impacts environnementaux de l'exploitation minière, pour ces raisons :

1. la réduction du volume de résidus nécessitant une déposition en surface diminue les impacts par la réduction de la superficie requise pour les opérations;
2. l'utilisation de tout l'ensemble des résidus dans la construction du remblai plutôt que de seulement la fraction grossière comme c'est généralement le cas pour le remblai de sable réduit la nécessité de manipuler et d'éliminer un flux de boues distinct;
3. la possibilité que les résidus s'oxydent ou soient lixiviés est réduite étant donné la nature des résidus épaissis servant de remblai souterrain, pour ces raisons :
 - la diminution de la quantité d'eau fait baisser la production de lixiviat;
 - l'oxygène disponible est réduit par un degré de saturation plus élevée;
 - l'écoulement préférentiel de l'eau souterraine se fait autour du remblai plutôt qu'à travers ce dernier par suite de la diminution de la conductivité hydraulique du remblai;
 - l'ajout de ciment accroît le potentiel de neutralisation et diminue la porosité réelle; et
 - l'éventuelle inondation à la fermeture de la mine réduit l'oxydation du sulfure à long terme.

Les théories générales quant aux caractéristiques et à la réactivité géochimique du remblai en pâte semblent reposer sur des bases scientifiques solides, mais il semble que peu de validation sur place de l'influence réelle des principaux paramètres soit réalisée. L'absence de conditions contrôlées dans les mines en exploitation semble limiter grandement la capacité d'évaluer séparément les éventuels enjeux en matière de mise à l'échelle. Le domaine a besoin de recherches visant la théorie des composants particuliers de la pâte (par exemple, dissocier l'influence de l'épaississement et de l'ajout d'un liant), d'un examen des enjeux en matière de mise à l'échelle (de préférence, dans l'environnement contrôlé d'une chambre remblayée qui est isolée, bien caractérisée et instrumentée), d'une collecte d'études de cas détaillées et d'un suivi supplémentaire des eaux d'exhaure afin d'évaluer l'influence du remblai en pâte sur la qualité de ces eaux au fil du temps. L'actuelle absence d'information détaillée est préoccupante et révèle la nécessité de compiler les données détaillées recueillies pour les divers sites et les données de suivi en vue de l'évaluation et de la validation futures des prévisions actuellement élaborées. Enfin, comme c'est le cas dans tout domaine nouveau, il serait utile d'établir une banque de terminologie qui servirait de norme.

Du point de vue général, il faudrait peut-être mieux définir l'éventuelle importance de la géochimie du remblai en pâte, de sorte que les priorités pour l'étude de cette question puissent être évaluées. Par exemple, est-ce que des mines déjà remblayées produisent

d'importants panaches de contamination de l'eau souterraine? Les mines situées à flanc de montagne qui continuent à se drainer à partir des ouvertures sont certes reconnues pour être d'éventuels problèmes au moment de leur fermeture en absence de restauration appropriée (c.-à-d. la mine Britannia, en C.-B., au Canada; la mine Summitville, au Colorado, aux États-Unis). Enfin, l'information disponible permet de croire que les mines remblayées pourraient éventuellement avoir des impacts lorsque la paroi souterraine et le remblai sont particulièrement réactifs (c.-à-d. Bernier and Li, 2003). Toutefois, un relevé général des mines souterraines existantes pourrait mettre en perspective l'importance de cette question.

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LIMITATIONS OF REPORT

This report was prepared by Mehling Environmental Management Inc. (MEMi) for the MEND Program. The material in it reflects the judgement of MEMi staff in light of the information available to MEMi at the time of report preparation. Any use which a Third Party makes of this report, or any reliance on decisions to be based on it are the responsibility of such Third Parties. MEMi accepts no responsibility for damages, if any, suffered by any Third Party as a result of decisions made or actions based on this report.

1.0 INTRODUCTION

Mehling Environmental Management Inc. (MEMi) was requested by the MEND (Mine Environment Neutral Drainage) Program to prepare a brief summary pertaining to current practices in the geochemical characterization of both cemented and uncemented paste backfill, and methods used to predict environmental impacts to surface and ground water quality associated with the application of paste backfill in underground applications.

Paste backfill is becoming a more common means of providing structural support in underground mines. The use of the mill tailings eliminates the need to provide quarried rock for structural support, and/or allows the removal of ore pillars that might otherwise need to be left for structural support. The use of tailings as backfill also eliminates the need to store this material on surface reducing the environmental footprint. The underground environment may be beneficial for the storage of sulphide tailings, potentially providing intimate mixing with alkaline binders and low oxygen conditions during operations. At closure, if the underground workings permanently flood, the potential for oxidation and the continued release of acidity and metals from high sulphide tailings can be significantly reduced.

Research to date has generally focused on the structural characteristics of the paste, in terms of meeting the required strength using the most economic amount and mix of binder materials. The geochemistry, including weathering and leaching of the paste materials, has been studied to a lesser extent.

Deleterious geochemical interactions may occur to affect the underground regime:

- Minerals may be present in the tailings, or produced by the tailings (i.e. sulphate, gypsum) that can act to reduce the long-term strength of the backfill, resulting in reduced mining efficiencies and potential subsidence after closure; and,
- Conditions in the underground mine may allow minerals in the tailings and/or binder to oxidize or react, producing soluble contaminants that may influence mine water quality produced during operations, or provide a contaminant source after closure, with the potential to adversely impact ground water and/or surface water quality.

Placing mine wastes back into their original environment initially appears attractive because the original material was stable in that environment. However, Ouellet et al. (2006) caution that the environmental impact should not simply be displaced from the surface to the underground. The backfill can oxidize during operations to produce metals and secondary mineral precipitates that are more soluble than the original minerals (Levens et al., 1996), and the backfill can be oxidized more readily due to increased permeability and surface area.

Under extreme conditions (Wheeland and Payant, 1991), backfill materials may be so reactive that they spontaneously combust to produce sulphur dioxide gas. Contaminated mine water is generally pumped to surface during operations and handled as a surface effluent. At closure, the mine usually floods and the backfill can provide a finite source of contaminants that can leach into the ground water system. Where closure does not result in a fully flooded mine, as in sidehill workings, the unflooded backfill can continue to oxidize and provide a continued source of soluble products, draining to either surface water or influencing ground water in the region of the mine.

Assessment of potential environmental issues therefore requires characterization of the paste mixture in terms of mineralogy, buffering and acid generating capacity, kinetic reactions and metal leaching potential, such that predictions of short and long-term effects on surface and ground water quality can be made.

This project summarizes available literature and case studies describing the characterization of paste backfill (tests, methods and results) and how these data are used in the prediction of potential long-term ground water, or chemical, effects. The report also provides some insight into long-term physical effects, as the two aspects are linked.

2.0 BACKGROUND

The question of how to include the influence from mine backfill on mine water quality predictions initially arose from MEMi's early participation in the development of Eskay Creek Mine's long-term closure plan. At the Environmental Assessment stage, characterization of the ore and waste rock had identified a significant portion that was potentially acid generating. In fact, a portion of the waste rock excavated during development of the exploration decline rapidly generated acidic drainage when stored on surface (Morin et al, 1997). Thus, mitigation plans were developed to permanently store waste rock underwater in a small alpine lake. When the mine began production, it was anticipated that the mine water would be influenced by acidic drainage and associated metal leaching from the workings and wall rock. Instead, the mine water proved to be highly alkaline (combined mine water at pH 10, with specific underground sites as high as pH 13), with antimony becoming the metal of concern due to its mobility under alkaline conditions (Barrick, 2002). The concrete backfill, composed of 4 to 8% cement and inert river gravels, appeared to be influencing the mine water more than the potentially acid generating wall rock. But for how long would the cemented backfill provide this high level of alkalinity, and what amount of neutralization would be available over the long-term when the addition of fresh backfill ceased and the mine was closed, with only portions of it flooded?

Similar questions will likely arise, or have arisen, at other proposed or existing sites. Environmental Impact Assessments conducted on newly proposed mines in Canada now require predictions to be made of the mine water quality produced from underground workings during operations in order to identify required mitigation alternatives, such as treatment, prior to discharge. Predictions of mine water quality after reclamation and closure are also required, in order to assess potential impacts to surface water from continued mine water discharges, and/or impacts to surface or ground water from the flooded workings.

It was not immediately clear how other sites were handling long-term predictions of mine water quality, particularly while addressing the influence of alkaline additives to their backfills. Furthermore, it was considered that the use of high sulphide tailings as a backfill could offset or overwhelm the impacts of any cement in the paste, unlike the effect noted at Eskay Creek where inert river gravels were used. Following discussions with MEND, addressing the influence of paste backfill on mine water quality was identified as one of the priorities.

Paste backfill is becoming a common means of providing structural support in underground mines, and also serves as a storage alternative for tailings waste. Paste backfill potentially utilizes the full grain size range of the mill tailings thickened to the consistency of toothpaste. Paste has been defined as "... a dense, viscous mixture of tailings and water that, unlike slurries, does not segregate when being transported" (Verburg, 2002). It may or may not incorporate strengthening additives and/or binders, such as cement. Thus the term tailings paste is essentially 'thickened' tailings, as championed by E.I. Robinsky in the early 1970's (Robinsky, 1975; Robinsky et al., 1991).

Claims have been made by the proponents of thickened non-cemented paste that acid rock drainage (ARD) should be substantially reduced, and potentially eliminated, as a result of the thickening process. Experience at Kidd Creek near Timmins, Ontario, indicates that thickening of the tailings may reduce, but has not been sufficient to eliminate, ARD production and contaminant release (St-Arnaud and Woyshner, 1993). Unfortunately for the industry, little quantitative data directly comparing thickened to unthickened tailings appears to have been collected and published.

Thus, the major aspects of underground paste backfill can be broken into three key questions that would appear to dictate its potential to influence mine water quality, assuming that the reactivity of the tailings has already been examined. These are:

1. How does thickening the tailings to a paste alter its geochemical reactivity?
2. How does the addition of binders, such as cement, influence the paste's reactivity and resulting leachate products?

3. How do the conditions in the underground environment influence reactivity of the paste?

Finally, the question of how to apply these three concepts to the prediction of mine water quality, during operations and after closure, must be addressed.

3.0 TAILINGS PASTE THEORY

All the usual factors associated with any backfill need to be addressed (Wheeland and Payant, 1991) when considering the use of paste, including:

- Capital and operating costs;
- Placement method;
- Mine configuration;
- Mining method;
- Engineering properties (if intended to provide support); and,
- Reactivity of the backfill materials, including potential oxidation of the sulphide minerals.

The movement of air and water through and around paste backfill is key to determining the extent of oxidation that could occur during operations and after closure, and the rate at which metals or soluble secondary minerals may be released to mine water and or ground water after closure. Factors which are likely to influence air and water movement include: paste grain size distribution, mineralogy, density, degree of saturation, permeability (to both air and water), binder or additive chemistry, the amount of binder added, tailings pore water chemistry (particularly sulphate content), and initial and altering engineering properties which will affect the extent of shrinkage, crack development and disintegration. Other aspects that will also affect air and water flow through or around the paste backfill are the characteristics of the host rock, placement of the paste (i.e. presence of voids between the host rock and backfill), and conditions under which the paste is stored in both the short and long term.

3.1 Benefits of Paste Backfill

The literature notes the potential benefits of using paste backfill, as compared to other potential backfill materials. These benefits include (Verburg, 2002; Bertrand, 1998; Levens et al., 1996; Deschamps et al., 2006)):

1. Reduction in the volume of tailings requiring surface disposal, thereby reducing surface impacts through footprint reduction;

2. Use of the full tailings stream in the backfill, rather than the coarse fraction used in more conventional sand fill, thereby reducing the need to handle a separate slimes stream;
3. Reduction in the potential for tailings to oxidize or leach due to the nature of thickened tailings placed as underground backfill because of:
 - Less free water, which reduces leachate generation;
 - Less available oxygen as a result of the higher degree of saturation;
 - Preferential flow of ground water around backfill, rather than through it due to the lower hydraulic conductivity of the paste backfill;
 - The addition of cement that provides extra neutralization potential (NP) and decreases effective porosity; and,
 - The potential for flooding at closure which reduces sulphide oxidation in long-term.

These identified benefits are discussed in more detail below.

3.2 Physical Attributes of Paste

Tailings paste backfill allows the use of the full tailings stream, including the finer portion. Traditional hydraulic placement tended to use only the coarse sand fraction in order to promote rapid draindown and avoid backfill stability issues associated with excessive water retention. Recent technological advancements in dewatering and pumping systems allow for controlled and consistent production and delivery of paste in a cost-effective manner (Verburg, 2002). When being transported either by gravity or through pumping, paste produces a plug flow with the fine particles creating an outer annulus thereby reducing friction. The coarse particles are forced into the centre of the conduit with the finer fraction acting as the carrier (Verburg, 2002). To facilitate pumping and placement, and to minimize scouring of the pipe used to transport the paste, Landriault et al. (1998) recommends that the backfill contain a minimum of 15 to 20% solids finer than 20 μm .

Benzaazoua et al. (2002) provides some guidance to understanding the hardening phenomena of paste backfills. Cement dissolution tests show that a major part of the total added cement (up to 20%) dissolves rapidly from the mixture. Benzaazoua et al. (1999) also showed that chemical alterations could seriously affect the long term strength of the backfill. They concluded that both mechanical and chemical aspects must be studied at an early stage as the chemical alterations can have a negative impact on backfill strength.

3.2.1 Air Permeability and Degree of Saturation

A higher degree of saturation typically results in less available oxygen, and therefore, less sulphide oxidation and reactivity associated with the tailings mass.

As described by Levens et al. (1996), the permeability of porous materials, such as paste backfill, to air is a function of the pore geometry and the amount of water in the pores. Geometric properties of pores include porosity, shape and dimension of pore spaces, and the tortuosity of flow pathways through interconnected pore spaces.

The amount of water in the pores, or the degree of saturation, is also controlled by the pore geometry. Materials with smaller pore spaces typically retain more water in the pore spaces under drained conditions due to higher capillary suction. This results in a higher degree of residual saturation, and a larger fraction of the pore spaces that do not contribute to effective flow through the material. Residual saturation ranges from 0.05 to 0.40, and is reached when water is held in pores that are smaller than the majority of pores (Levens et al., 1996). The degree of saturation in backfill can increase above residual if water continues to flow into the backfill from the host rock. If flow into the backfill is sufficient, the backfill can become completely saturated, reducing oxygen ingress to that which is dissolved in the incoming ground water.

3.2.2 Water Permeability

A reduction in permeability of the tailings should reduce the amount of water moving through the tailings, and reduce the rate at which soluble contaminants are transported from the tailings backfill. Paste backfill is of benefit in this regard, since paste tends to include the finer tailings grain sizes in a relatively homogeneous manner, and therefore should have reduced permeability relative to unthickened tailings (Levens et al., 1996). The addition of cement further reduces the permeability in the fill (Levens et al., 1996) as the hydrated cement minerals serve to isolate the pores in the tailings mass and decrease effective porosity.

At the larger scale, backfilling of underground workings with any material should reduce permeability (as compared to open workings), increase the long-term water table elevation, and lead to a lower level of long-term oxidation and contaminant release (Kistinger, 1997). However, in flooded mines where the host rock has low hydraulic conductivity, the backfill stopes may still constitute the preferential flow path.

As described by Levens and others (1996), water flow through cemented backfill that has shrinkage cracks or gaps at rock-backfill interfaces will behave in a similar manner to fractured porous rock. The intact backfill and the secondary cracks and openings will have

different relationships governing the air permeability, and the degree of saturation, and these will vary depending on the amount of water inflow from the host rock. Under dry conditions, water will be held in the intact backfill and the secondary cracks or openings will be dry, potentially allowing partial oxidation in the intact backfill (depending on air permeability and availability) and full oxidation of the fracture surfaces. Under wetter conditions, flow through the larger openings or cracks will increase. When backfill is flooded after mine closure, flow will be primarily through the secondary openings or cracks. Therefore, the surface area available for oxidation will be less under wetter conditions, but the formation of shrinkage crack and gaps will increase oxidation when they are drained under relatively dry conditions.

3.3 Tailings Geochemistry

Underground conditions may reduce the reactivity of tailings minerals, thereby limiting production of ARD or soluble contaminants. However, minerals present, or produced through chemical interactions with binders, may also reduce the long-term strength of the paste, with potential for:

- Reduced mining efficiencies and decreased safety; and,
- Changes to ground water flow patterns through the paste, as porosity typically increases in association with reduced strength.

There are also inherent limits to the reactivity of the materials that can safely be placed underground. For example, Wheeland and Payant (1991) proposed preliminary screening criteria for tailings to be used as backfill to assess the risk of auto-ignition and potential for adverse effects on engineering properties. Development of these criteria were instigated due to an incident at Brunswick Mine in New Brunswick where the use of some high sulphide slimes as uncemented backfill in the upper sections of the mine resulted in a fire that 'burned'. This produced sulphide dioxide gas for over two decades, despite efforts to establish bulkheads to limit air ingress (Wheeland and Payant, 1991). The established criteria were as follows:

1. *If the mineralogy, or experience, indicates the possibility of reactivity, two tests will be conducted on representative samples:*
 - *BC Research Acid Generating Potential Test*
 - *Thermo-monitoring Weathering/Self-heating Test (TMT). This is a procedure developed by Noranda which involves weathering of a damp 1 kg sample for 2 days at 75 degrees C with intermittent air sweeps, raising the temperature to 140 degrees C and monitoring the rate of temperature rise when air is intermittently passed through the sample.*
2. *If both are negative, no further testing is required.*
3. *If either is positive, further TMT tests will be conducted with screen fractions.*

4. *If any of these are positive, further TMT tests will be conducted on various blended backfill materials (uncemented) to establish no-risk composition for auto-ignition (tentatively 25% of observable self-heating).*
5. *Standard leach tests (CGSB Provisional Standard No. 164-GP-1-MP. Leachate Extraction procedure 1987) will also be conducted on set backfill if the BC test is positive.*

Evaluations of reactivity have led to a general rule of thumb, whereby target pyrrhotite concentrations in the backfill are kept to 14% or less to avoid significant self-heating (Moerman et al., 2001).

The surrounding host rock, as well as the tailings themselves, may be affected by heat generated by oxidation of high sulphide tailings. Morin and Hutt (1995) suggest that the heat may alter conditions of the host rock, such as the degree of fracturing and mineral precipitation/dissolution reactions.

The effects on tailings geochemistry can be quite extreme. Bernier and Li (2003) examined fresh and highly oxidized paste backfill specimens from three underground mines. Acid-base accounting data at various stages of oxidation are shown in Table 1, Table 2 and Table 3. Mineralogical examinations indicated significant mineral alteration at temperatures estimated to be below 100 °C for the yellow to orange paste specimens, and to be greater than 250 °C in the red paste specimens from the three sites. Bernier and Li (2003) noted that "... the degree of oxidation is quite surprising, as paste backfill is normally considered non-reactive due to its low permeability to oxygen and alkaline pH." Thus the general theories put forward promoting the benefits of paste backfill do not preclude the potential for significant oxidation when placed in underground workings, nor do they preclude the potential to significantly influence mine water chemistry during operations, and/or after closure. Thus, a thorough geochemical characterization must be conducted before a decision is taken to dispose of tailings in paste form (Verburg, 2002).

3.4 Cement and Other Binding Additives

Cement or other additives such as fly ash or slag are blended into a paste in order to increase the short or long-term physical strength of the cured material. Increasing the strength of the backfill allows mining in the immediate vicinity of the backfill, and reduces the amount of dilution of ore when blasting or excavating next to backfilled areas. Other identified benefits associated with the addition of binding additives are:

- A reduction in the permeability of the bulk paste;

- A reduction in leachate production, and/or bleeding of the backfill once in place, since cement hydration uses water;
- Provision of an initially alkaline environment, reducing the solubility of many metal ions;
- Addition of extra Neutralization Potential (NP) associated with the additive, which may potentially reduce the rate of oxidation of the waste through intimate blending (Mehling, 1998), buffer the acidic oxidation products produced from sulphides in the paste, and/or neutralize acidic drainage produced by other reactive areas of the mine.

However, the presence of sulphides and/or sulphate associated with mine tailings tends to have a deleterious effect on the ability of the cement to set, and on the long-term durability of the concrete mixture (Bertrand, 1998). Residual process water held in the thickened tailings, and the environment into which the paste backfill is placed, also tend to contain high sulphate concentrations detrimental to the physical strength of the concrete (Bertrand, 1998). Sulphates react with the hydrated cement to produce expansive minerals, such as gypsum, that cause the material to crack and lose strength. Other additives, such as slag, are used to increase resistance to sulphate solutions by minimizing reliance on portlandite as a binder (Bertrand, 1998).

Although additional neutralization potential is provided to the paste by the addition of cement, seldom is enough added to alter the ratio of neutralization potential to acid generating potential (Neutralization Potential Ratio or NPR) or acid generating classification of the backfill material (Bertrand, 1998). Also the components of hydrated cement are readily dissolvable, such that, while providing effective NP in the early stages of mine life, the effective buffering minerals are likely to be rapidly depleted. Fully cured paste is more resistant to loss of binder minerals, so it is beneficial to place fresh paste in dry areas where leaching solutions are not immediately contacting the paste.

Studies with paste backfill suggest that it is the accessible surfaces of the paste backfill (i.e. the edges of the backfill which are in contact with water) that are more likely to be affected. The paste is altered in progressively developing concentric layers, with the cores of the flooded paste backfill samples undergoing the least amount of alteration (DeCeukelaire, 1991; Revertégat et al., 1992; Kosmatka et al., 1995; Casanova et al., 1996; Bertrand, 1998). Depletion of the binder minerals, such as portlandite ($\text{Ca}(\text{OH})_2$), results in increased porosity such that paste strength is reduced and fluids in the mine (ground water/ARD) can penetrate more easily into the paste mass.

3.4.1 Cement Chemistry

The following summary is adapted from Bertrand (1998).

Cement is one of the most commonly used materials in the construction industry and much is already known about its chemistry, its strengths and weaknesses and its interaction with a variety of aggregates (Taylor, 1997). Under normal circumstances, the inherent chemical stability, physical strength and workability of concrete allow its use in a variety of settings. Table 4 describes the various elements that make up Normal or Ordinary Portland Cement (OPC) typically used in cemented paste backfill, along with the principal hydration reactions involved in the curing of cement mixtures. Pore water in concrete typically has a stable pH of about 12, associated with portlandite ($\text{Ca}(\text{OH})_2$), a by-product of cement hydration.

Some agents are known to interact destructively with the components of the concrete, undermining its integrity. Of these, reactive mineral aggregates (i.e. sulphidic aggregates), high concentrations of sulphate in the mixing water or excess atmospheric CO_2 upon drying make up the principal destabilizing agents of concrete (Kosmatka et al., 1995). These processes are:

- Carbonation;
- Alkali-Aggregate reactions;
- Sulphate attack; and,
- Water dissolution.

These are briefly described in the following paragraphs.

Carbonation

Carbonation refers to the excessive shrinkage of concrete upon drying caused by the penetration of atmospheric CO_2 , transforming hydroxides to carbonates. These reactions lower the alkalinity of concrete, destabilizing the curing process. High water/cement ratios, low cement content and/or a short curing period enhance the potential for carbonation to occur. This phenomenon is normally restricted to shallow depths or at the surface of the concrete.

Alkali-Aggregate Reactions

The reaction between reactive mineral aggregates used in the concrete mixture and the sodium and potassium alkalis present in the cement cause expansive secondary mineral

growth. Growths of secondary minerals create internal stresses within the concrete causing it to crack and lose its strength. CANMET has examined these reactions indirectly for a number of years (i.e. shotcrete covers over reactive rock surfaces and mine tailings: Malhotra, 1991), and more recently in the context of backfills (Kwong, 2004).

Sulphate Attack

The interaction of sulphate ions present in the pore water with the hydrated compounds of the cement also results in expansive secondary mineral growth (gypsum and/or ettringite) combined with disintegration of the primary binding material (tobermorite gel).

Water Dissolution

Another deleterious agent of particular importance in the backfill environment is the interaction of neutral pH water with concrete. It can dissolve and leach out some of the pH sensitive or water-soluble components of hydrated cement such as portlandite ($\text{Ca}(\text{OH})_2$) or tobermorite gel ($\text{Ca}_3\text{Si}_2\text{O}_7 \cdot 3\text{H}_2\text{O}$). This can be particularly deleterious when contact occurs during the curing period of the freshly mixed cement (Adenot and Buil, 1992; Carde and Francois, 1997).

3.4.2 Characteristics of Cemented Tailings Backfill

The following summary is adapted from Bertrand (1998) and provides an overview of the principal differences between cemented tailings and regular concrete mixtures and how these may affect the physical and chemical stability of cemented backfill.

Binder Content and Strength Development

The strength requirement for paste backfill depends on the purpose of the backfill. In general, strength requirement for backfill are much lower than for average concrete mixtures. Backfill used to fill empty voids surrounded by rock requires minimal strength, essentially enough to prevent liquefaction when blasting other areas of the mine or in the event of seismic activity. Higher backfill strengths are required when the paste backfill is used to support rock faces against which active mining is planned.

In general, the processes that lead to a reduction in strength are potentially significant for the paste geochemistry in that breakdown of the paste provides more accessible surface areas for oxidation or other geochemical reactions to occur. This also increases the permeability of the backfill so that reaction products are more easily released.

A very small amount of cement is normally used to bind tailings as compared to concrete. Commonly less than 10% or even 5% of dry weight is used, as compared to common concentrations of cement in concrete ranging from 30% to 40%. In addition, the water to cement ratio, important in the hydration and subsequent curing of cement, are also considerably higher in cemented paste backfill applications, as compared to concrete. This ratio is expressed as the mass of water divided by the mass of cementing materials. Kosmatka and others (1995) explain that lower water/cement ratios provide significantly higher unconfined compressive strength in normal concrete. Lamos and Clark (1989) came to the same conclusion with respect to tailings backfill. Normal concrete water/cement ratios, typically around 0.5, yield 28-day unconfined compressive strength values ranging between 25 and 35 MPa. Typical cemented paste backfill applications (such as the four studied by Bertrand, 1998) have water/cement ratios ranging from 5 to 10 and have unconfined compressive strength varying from 0.05 to 3.5 MPa. Cemented paste backfill mixtures can, therefore, be expected to develop poorer unconfined compressive strength values upon curing than concrete containing the same amount of cement.

In addition, the tailings mixed with the cement to form paste backfill is regarded in the cement industry as undesirable aggregate because of its very fine grain size. The Canadian Standards Association (Standard A23.1) specify the lower and upper limits of grain size that should make up the fine size portion of aggregate, and specifies a lower limit of 5% to 10% passing 160 μm and an upper limit of 80% to 100% passing 2.5 mm. Furthermore, the Canadian Portland Cement Association (CPCA) (Kosmatka et al., 1995) indicates that the fine aggregate content should be no larger than 45% by mass or volume of the total aggregate content, above which the cement cannot efficiently coat all aggregate particles, and meet specified strength requirements.

In the case of cemented paste backfill, the tailings used as aggregate are often finer than 150 μm , and at minimum should contain 15% to 20% solids finer than 20 μm (Landriault et al., 1998). Empirical and operational data suggests that a paste must contain at least 15% by weight passing 20 μm to exhibit the typical paste flow properties and retaining sufficient colloidal water to create a non-segregating mixture (Verburg, 2002). Consequently, the cement added to the paste mixture can be expected to under-perform in terms of strength development upon curing compared to a similar cement proportion used in conjunction with standard aggregate.

Aggregate Type and Sulphate Reactions

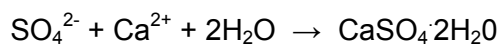
Pyritic aggregate is normally avoided in cement mixtures because of its reactivity and the consequent production of sulphates. Pyrite and other sulphate-generating minerals are often

present in the tailings used for paste production. Sulphate is a documented aggressive agent that participates in expansive secondary mineral growth within the concrete (Shayan, 1988; DeCeukelaire, 1991; Idorn, 1992; Casanova et al., 1996). These reactions create internal stresses that lead to cracking and disintegration of the cured concrete.

Sulphate is also present in the residual mineral processing water in the thickened tailings used to form paste. Cemented paste backfill is normally made from tailings piped directly from the processing plant, to which cement is added. Sulphate in mineral processing water is often in concentrations greater than 1.5 g/L, which would constitute 'severe' exposure in the cement industry (Table 5). The hydration water of the mixture consists in large part of sulphate-rich residual process water. The only method of reducing the sulphate concentration in the tailings water would be to thoroughly wash the tailings with clean water, or precipitate out the sulphate as a stable mineral phase, both of which are uneconomical and inefficient (Noranda Technology Centre, 1998). The presence of sulphate in the mix water, or as a by-product of pyritic tailings oxidation, results in chemical stress being generated within the paste, and can lead to cracking. In a mine setting, the backfill may also be externally attacked by sulphate-rich acidic drainage generated within the mine, leading to physical breakdown of the paste.

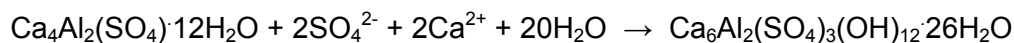
The chemical process of sulphate attack on hydrated concrete can be summarized as follows (Bertrand, 1998):

Free sulphate ions present in solution can combine with calcium of dissolved portlandite to form gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) according to the reaction:



Gypsum growth in pore spaces creates pressure that, when occurring at large scale, can induce cracking of the backfill. Crystallization pressures can reach 70 to 2000 MPa (Ouellet et al., 1998).

The creation of ettringite is also an expansive reaction that can result in cracking and disintegration of the backfill (Fu et al., 1995; Taylor, 1997). Ettringite, ($\text{Ca}_6\text{Al}_2(\text{SO}_4)_3(\text{OH})_{12} \cdot 26\text{H}_2\text{O}$), forms from the reaction of aqueous sulphate and calcium (from dissolved portlandite and free sulphate, or from dissolved gypsum), and the monosulphate phase of cement ($\text{Ca}_4\text{Al}_2(\text{SO}_4) \cdot 12\text{H}_2\text{O}$) according to the following reaction:



Mineral additives such as ground blast furnace slag, silica fumes or fly ash can be added to partially replace Portland cement. These additives modify the fill mixture properties such as workability, increase the strength of the fill at a particular stage of curing, or increase

resistance to chemical attack (Mangat and Khatib, 1995; Gifford and Gillott, 1997; Taylor, 1997). Mineral additives such as those presented in Table 6 are used to reduce the cost of the binding agent without decreasing the strength of the fill. In order to improve the sulphate resistance of concrete, the amount of calcium hydroxide and calcium aluminate hydrate must be minimized. Blast furnace slag with a relatively low iron content is favourable for use against sulphate rich waters (Kosmatka et al., 1995). However, the use of mineral additives does not provide the increased alkalinity associated with the addition of cement.

Backfill Porosity and Binder Dissolution

Once placed underground, dissolution of the cement phase of the paste backfill can occur to varying degrees, leading to increased porosity and decreasing strength. The considerably higher porosity of backfill compared to concrete suggests that leaching solutions will more effectively penetrate the backfill and influence the pore solution chemistry. This will create chemical inequilibrium conditions between the pore solution and the solid phase of the backfill and accelerate the dissolution of the cement phases of the backfill (Bertrand, 1998).

Dissolution of the cement phase of cemented containers of nuclear waste have been studied by the French Commission on Atomic Energy, with the following results (Bertrand, 1998):

- Carde and Francois (1997) noted that an ammonium nitrate solution leached the cement in a similar manner to, but more rapidly than, water. They noted that a zone of lesser strength formed in the leached areas and that the decreased strength was due to increased porosity resulting from the complete leaching of the portlandite ($\text{Ca}(\text{OH})_2$) phase of cement. The increase in porosity was calculated to be equal to the proportion of portlandite in their concrete mixtures. A progressive decalcification of the tobermorite phase ($\text{Ca}_5\text{Si}_6\text{O}_{16}(\text{OH})_2 \cdot 4(\text{H}_2\text{O})$) was also observed, typically linked to losses of binder volume and material strength. Leaching of these phases was the only deterioration found to occur in concrete samples kept immersed in the ammonium nitrate leaching solution. In wet-dry cycled experiments, an increase in pore solution ion concentration was found to promote the precipitation of secondary expansive minerals such as ettringite causing internal stresses and micro-cracking of the concrete;
- Adenot and Buil (1992) used deionized water in similar leaching experiments and observed similar alteration: thin leached zones characterized by partial or complete dissolution of portlandite, but preceded by the dissolution of ettringite and monosulfoaluminate phases. Calcium to silicon ratios of the tobermorite phase were also found to decrease from the core of the specimens towards the surfaces, reflecting decreasing calcium concentrations in the pore solution near the edges of the samples.

Advancement of the dissolution front was calculated to be proportional to the diffusion rate of deionized water in the concrete. The cores of their flooded samples were observed to be compositionally unchanged; and,

- Revertégat and co-workers (1992) conducted similar leach experiments with deionized water, finding that the deionized water was effective in dissolving portlandite, thereby increasing the porosity of the material, as well as decalcifying or degrading tobermorite gel, the principal binding agent of cement. They determined that the dissolution of portlandite started to occur at pH 12.5 and became more severe as the pH of the pore solution dropped. Samples made with a binder mixture of cement and fly ash showed an increased resistance to leaching. They determined that the cement/fly ash binder mixture used portlandite in its hydration process, effectively decreasing the amount of portlandite available to be leached, resulting in a lower loss of porosity.

3.5 Underground Environment

Conditions in the underground environment differ from laboratory or surface conditions, and, as such, are likely to affect the reactivity of the paste backfill. Morin and Hutt (1995) noted that placement of tailings themselves as underground backfill would change the conditions in the underground workings. The changes would primarily affect the reactivity of the tailings and wall rock, subsurface water quality, underground water flow, and underground air quality. These factors along with temperature were noted as being interactive, such that a change in one factor could affect one or more of the others.

During operations, paste backfill is typically located in unflooded areas, since the water table is typically pumped below the workings. At closure, the paste backfill may either remain in an unflooded state above the water table, or could lie within a fluctuating water table, or be permanently flooded in a location below the water table.

Water quality in underground mines is often not considered in detail, as the mines are assumed to be flooded such that continued long-term oxidation of the sulphides in the wall rock and backfill will be negligible. However, issues may arise where anion-forming constituents (e.g. antimony, arsenic, selenium, etc.) are present in ground water, host rock or cemented tailings backfill, and the higher pH of cement-affected mine water increase the mobility of these constituents. The Eskay Creek mine is an example where, although ARD, was minimized, the cemented backfill created a new water quality issue (elevated aqueous antimony concentrations). The issue of long term mine water quality may be more critical in side hill mines, where there is a potential for a greater portion of the workings to remain unflooded, and for water to continue to flow from the workings after closure. In this case,

continuous generation of ARD could develop after the alkaline buffering has been leached away.

Backfilled stopes drain during operations, due to the ground water table being drawn down. Soluble secondary mineral salts produced from the neutralization of ARD will certainly influence operational mine water quality, but a substantial portion may remain in the mine. During closure, as portions of the mine reflow, these stored oxidation products can be released to the rising water. If the mine is totally confined (Figure 1), this may lead to a slow migration of contaminants into the ground water system. However large flows and high concentrations would not be expected after the initial release of secondary mineral products. Under stagnant or reducing conditions in the reflooded mine, soluble oxidation products may even precipitate as less soluble forms (Steffen, Robertson and Kirsten (B.C.) Inc., 1987). In side hill mines (Figure 2), a portion of a mine may remain drained, with continued production of oxidation products associated with potentially higher concentrations and flows, and higher long-term consequences.

Conditions unique to the underground environment that are relevant to reactivity of the paste and its influence on mine water quality are briefly discussed in the following sections.

3.5.1 External Attack by Ground Water or ARD

Paste placed as underground backfill is exposed to ground water and mine water flows, such that soluble components on the exposed surfaces are constantly flushed.

Sulphate is present in most metal mines, either in the ground water in contact with the deposit or in the waste water generated by ore processing. Acid rock drainage (ARD) may also be present, with acidic solutions and high (aggressive) concentrations of sulphate generated by the oxidation of sulphide minerals (Section 3.4.2). The bathed surfaces of the paste backfill are susceptible to the acidic attack, the leaching of alkaline minerals (from cement additives or the paste minerals), and the formation of expansive minerals that enhance disintegration.

3.5.2 Oxygen Availability

Kinetic tests are typically run in a laboratory environment where oxygen is readily available. However, paste tailings placed as backfill in underground environments may have less available oxygen and may experience different curing conditions (for example lower evaporation rates) in comparison to surface deposited pastes.

The availability of oxygen has a direct influence on the quantity of soluble secondary oxidation products that may be produced. Reduction in oxygen availability may reduce the

generation of ARD, but ARD may not be eliminated, and consequently, the need for treatment of mine water and/or ground water after mining has ended may not be eliminated.

A specific volume of oxygen is present in the pore spaces of the paste when it is placed, with additional air initially present in:

- Internal voids in paste mass;
- Gaps against underground walls;
- Fractures in the wall rock; and,
- Gaps between successive paste campaigns (joints), or incomplete fills.

Some of this initial oxygen can be replenished through:

- Links between adjacent stopes;
- Exploration and underground drill holes intercepting the stopes;
- Active mine ventilation; and,
- Oxygen contained in inflowing ground water.

The extent of the pore spaces can generally be estimated from data available from tests on the strength and/or density of the paste backfill. Typically, the paste is assumed to be saturated when it is placed, with minimal ingress of air into the portion of the paste that drains down to residual levels. The extent of gaps associated with placement of the paste does not appear to be quantified in the literature. And there appears to be differing opinions as to the ability of air to be replenished around the paste backfill during operations, and, in some cases, after closure. For example, a range in assumptions has been used in mine water quality predictions:

- Relatively free air ingress during operations (Barrick, 2002).
- Unsealed exploration drill holes reaching to surface, and incompletely sealed portals, shafts or vent raises suspected of potentially allowing relatively free air ingress after closure (Barrick Gold Corporation, 2002.)
- Oxygen access controlled by diffusion into the cemented paste backfill during operations, because the stopes are to be sealed with bulkheads (Chapman et al., 2003).
- Oxygen limited to that introduced by inflowing ground water at closure (Hockley et al., 1998).

Reporting of actual monitored oxygen concentrations in completed backfill workings appears to be extremely limited, although Ouellet et al. (2006) report on the use of oxygen meters in a

cemented paste backfill at the Laronde Mine in Quebec. They concluded the cement binder in the sulphidic paste backfill reduced oxygen migration and consumption, and limited the formation of ARD.

4.0 SURVEY AND FINDINGS

The influence of paste backfill on mine water quality, and the ability of thickening and additive chemistry to mitigate ARD may have a key economic impact on the mine closure scenarios. It would therefore be beneficial for management and the industry to assess how the use of cemented paste backfill can reduce long-term costs and reduce environmental impacts in general.

The following section attempts to describe the state of the art at present.

4.1 Survey Methods

To determine whether the influence of paste backfill on mine water quality was being studied, and how the influence of the paste backfill was being implemented in predictions of mine water quality, MEMi contacted 37 underground mines in Canada, the United States, Australia, Africa and Russia via telephone and emails through the fall of 2003. Canadian mines using paste fill, cemented rockfill or cemented mill tail as backfill were identified from the Canadian Mining Journal's 2002 Sourcebook. Other mines were identified in discussions with a network of consultants, industry and government representatives.

A questionnaire was submitted to the mines, asking the following questions:

- Do you have information on the geochemistry of your paste backfill?
- Have you used this information in the prediction of short or long-term mine water quality?
- Have you used this information in assessing the long-term strength of your backfill?
- Do you collect samples for geochemical analyses of mine water percolating/flowing from stopes backfilled with paste?
- Do you collect data on mine water quality from the mine as a whole that might be useful in evaluating the effects of paste backfill over time?

On the basis of the initial responses, general discussions with environmental staff were conducted for selected mines.

4.2 Survey Findings

The paste backfill survey findings are presented in Table 7. The table information includes which mines were contacted, mine location, mine status, paste information including type, binder and binder content, contact information and the answers to the five questions outlined above. The table was enhanced with information from literature where applicable.

The definition of paste backfill as thickened tailings, with or without added binders, was found to be insufficiently specific because the presence or absence of binders, such as cement, is known to play a significant role in the paste's influence on mine water quality. Thus, discussions below use the following terminology:

- **Paste backfill** = refers to all paste mixtures, i.e. thickened tailings, with or without added binder
- **Thickened tailings paste** = thickened tailings without added binder
- **Cemented tailings paste** = thickened tailings with added cement and/or other binder. Note that all paste mixtures with added binder utilized in the contacted mines included cement in their mixtures. The binder might consist of 100% cement, or a portion of the binder would consist of cement, with the remaining portion consisting of other materials, such as slag, or fly ash.

Paste Backfill

- 16 mines use or propose to use paste backfill, i.e. thickened tailings.
- 11 of the 16 use or propose the use of cemented tailings paste, with the addition of cement varying from 2 to 6.5%.
- 5 mines use no additives and rely only on thickened tailings paste.
- Of the 16 mines, only 4 appear to be conducting predictions for underground mine water quality.
- Only 2 mines directly monitor mine water flowing from the paste backfilled stopes.

Other Backfills

- 15 underground operations use backfill materials other than paste tailings, such as unthickened tailings, waste rock or aggregate mixed with cement.
- Cement content in the backfill mixes varied from 2 to 10%.

- Of the 15 mines using alternative backfill materials, only one appears to be conducting predictions for underground mine water quality.

Surface Paste Applications

Where paste tailings are being stored, or proposed to be stored, on surface, the assessment of paste geochemistry and its potential effects on surface and/or ground water appears to be more thorough:

- 7 mines are storing or proposing to store paste tailings production on surface.
- Cement content varies from 0 to 20%.
- 3 of these 7 mines indicate that a portion of their paste will be placed underground. The characteristics of the surface paste may differ from the underground paste portion, usually in terms of the added binder content.
- 6 of these 7 mines have conducted or are in the process of conducting leachate, seepage and/or runoff water quality predictions.

The placement of paste on surface appears to have enhanced the degree to which the geochemistry of paste has been studied. The emphasis on the study of paste for these sites may also be related to their relatively recent start-up dates, since more detailed assessments are now required. In any case, the selected case studies described in Section 5.0 tend to be drawn from mines which plan to store paste tailings on surface, as these sites appear to have more relevant detailed information.

4.3 Characterization Programs

Methods for characterization of paste backfill include the standard tests for geochemical characterization of mine waste, and include:

- Static acid-base accounting (ABA) analyses
- Chemical analyses (i.e. metals content)
- Mineralogical analyses
- Short-term leach tests
- Long-term kinetic tests

In reviewing the reported test programs, it appears that many laboratory characterization programs are conducted on un-thickened tailings from metallurgical test programs, since the

initial test programs do not evaluate the final thickening step. For the same reason, geochemical testwork on metallurgical test program tailings may not incorporate binder additives such as cement.

ABA and chemical analyses are often conducted on the additives and the tailings separately, although many ABA evaluations are conducted on the actual proposed mixtures. On occasions, ABA and metal values for the mixtures are estimated by proportional calculations assuming a percentage binder addition, rather than actual analyses.

4.3.1 Kinetic Test Methods

Given the porous, cohesive nature of cemented paste, kinetic tests conducted on paste backfill have required innovative means of preparing the material for column or humidity cell tests. For various projects (see additional details in Section 5.0), kinetic tests have been conducted on:

- Small cubes of moulded, cured paste, ranging in size from <1 cm to 3 cm cubes;
- Intact cylinders of paste; and,
- Crushed paste.

Tests include both typical humidity cell conditions (i.e. laboratory temperatures, 3-days dry air followed by 3-days humid air, followed by flushing with added water), and flooded or subaqueous conditions. Results have been reported both on the basis of mass (i.e. leach rates in mg/kg/week) and surface area (i.e. mg/cm²/week).

As typical for most geochemical tests, the results can be misleading if all test variables are not defined. Ideally, detailed test methods should be provided, along with as many details as possible regarding the test material, such as cement/binder content and composition, tailings mineral composition and grain size distribution, ARD potential and metal content; sample density and porosity. For cemented paste samples, the degree of curing prior to testing is an additional factor of significance. Tests have been performed on samples cured for the standard 28-day period typical of concrete tests, and on samples cured for shorter periods, which may be more typical of conditions in a mine backfill environment where backfill is placed underground shortly after mixing.

As an example, SRK conducted column kinetic tests on small (1 cm) moulded cubes of cemented pyritic paste and uncemented pyritic concentrate for the proposed Crandon Mine in Wisconsin (Chapman et al., 2003). The cement amended tailings paste cubes (5% by wt.) were allowed to cure for 28 days prior to loading into the columns for testing. Each column test consisted of about 700 to 800 cubes. The column tests were operated on a seven-day

wet-dry cycle, with humidified air being passed through the columns for six days, and the column being flushed on the seventh day with one litre of de-ionized water. Two of the three columns were operated for 20 weeks and the third for 107 weeks. From the results, SRK was able to determine:

- Solute release rates from cemented paste,
- The depth of oxidation in cubes (<1 mm over 107 weeks), which was likely limited by diffusion, and,
- That the oxidation reactions were surface reactions.

Results were therefore reported as mg/cm² surface area/kg sample. Secondary minerals, such as gypsum and iron-oxy-hydroxides, formed a distinct 'rind' at the surface of the paste backfill cubes, further emphasizing the need to evaluate the oxidation of paste backfill as a surface phenomenon.

Verburg et al. (2000) conducted a kinetic testing study on both intact one kg cylinders of cemented paste and crushed cemented paste, under both subaerial and subaqueous conditions, from an operating mine which was not identified. The mine is referred to as the 'unnamed' mine in this report. The crushed cemented paste samples were created by breaking intact cylinders in a manner that encouraged fragmentation along natural surfaces to sizes less than 1 cm. Kinetic testing of the intact paste and crushed paste were performed in humidity cells with the subaerial cells operated under conventional humidity cell conditions (3-days dry air, followed by 3-days humid air, and flushing on the seventh day with one litre of water). The subaqueous cells operated under near-anoxic conditions.

Laboratory Scale-up Issues

Most laboratory kinetic tests are likely to be poor simulations of in-situ conditions. For underground paste backfill, the laboratory tests are likely to differ from in-situ conditions in terms of climate (temperature, humidity, gas environment and access to oxygen), solution chemistry in contact with the paste, and solution application rates. Moreover, the test sample may differ from in-situ paste in terms of chemistry, density and porosity. Detailed characterization of the laboratory samples undergoing tests can assist in identifying critical factors that differ from laboratory and in-situ materials.

Surface field cells have been effectively used for the evaluation of surface disposal of paste, since these mimic the actual disposal environment (Verburg, 2002). This larger scale test may also be useful for identifying internal conditions within the bulk mass of a backfilled

paste, and some of the mechanisms governing paste weathering in oxygenated environments.

4.3.2 Weathering Characteristics of Paste Backfills

Bertrand (1998) conducted a weathering study on paste backfill samples from 4 different mines. The samples were created using formulations provided by the individual mines, and subjected to leaching after 14 days of curing in a humidity environment. Each sample was leached in deionized water (pH 5.5) in flooded and alternating air-flooded environments. A simulated solution representative of acidic drainage ($\text{Fe} = 500 \text{ mg/L}$, $\text{SO}_4 = 1.5 \text{ g/L}$, and pH 2.5) was used for the 20-week experiment. Bertrand found that:

- Hydrated Portland cement minerals are pH sensitive and highly soluble.
- NP provided by the addition of Portland cement is short lived, but cement content has a greater influence on the short-term leachate quality (i.e. first 20 weeks of leaching) than tailings composition.
- Surficial oxidation of paste samples made with high sulphide tailings (37% as sulphide-sulphur) and 6% cement by dry weight begins rapidly (within the 14 day cure period).
- Alteration fronts penetrated deeper in samples with higher pyrite even with associated higher binder content.
- Attack by acidic solutions created an increasingly thick crust of precipitates on the surface of the backfill, such that, with time, the ability of the cemented backfill to neutralize the acidic solution could potentially be reduced.
- Short-term exposures of cemented paste backfill to neutral or acidic solutions promoted the dissolution of the primary binder minerals, increasing the porosity of the backfill and enhancing the ability of the aqueous solution to enter and flush the backfill.
- Fully cured paste was more resistant to loss of binder material, such that it would be beneficial to place fresh paste in dry areas such that they are not subjected immediately to leaching solutions.
- Long-term exposure or flooding of cemented paste backfill promoted the precipitation of secondary, expansive minerals such as gypsum, in addition to the dissolution of primary binder minerals. Formation of expansive minerals creates internal stresses that would tend to accelerate the disintegration of the paste backfill, and increase the surface areas accessible to oxidation and release of soluble secondary minerals.

- Cyclic flushing of the backfill washed away the ions before supersaturation and precipitation of expansive mineral phases could occur, but resulted in accelerated loss of binder material at the paste surfaces, typically associated with increased porosity and loss of strength.

On the basis of laboratory tests, Kwong et al. (2005) concluded that the specificity of binders to suppress metal loading varies with the tailings composition and modes of occurrence of the pertinent chemical species. Detailed tailings characterization is thus indispensable in devising a proper binder to assure the short and long term chemical stability of tailings backfills at a mining operation.

Laboratory testing of paste backfills with and without the addition of sludge has been reported by Benzazoua et al (2006).

Surface Reactions

Although paste can apparently be produced with virtually no runoff water and tends to support high degrees of saturation that will reduce oxidation (Verburg, 2002), consideration must be given to surface reactions. As noted above in the kinetic test examples, the outer edge of paste is potentially susceptible to more intense oxidation and dissolution reactions than the interior bulk of the paste. This can result in physical, as well as chemical, changes. For example, the potential for spalling or disintegration of paste backfill surfaces and the resultant increase in effective surface areas susceptible to oxidation reactions was considered for a proposed paste mixture at the Crandon site (Chapman et al., 2003). They noted that there was only minor breakage of the edges of 1 cm cubes leached for 107 weeks in column tests. Alternatively, examination of developing weathering rinds under flooded and alternating wet and dry conditions found an accelerated loss of neutralizing minerals related to increased porosity and decreased permeability at the edge of the paste sample (Bertrand, 1998). Thus there is the potential for surface reactions to cause physical deterioration of the paste, potentially leading to more rapid chemical reactions and further physical disintegration.

4.4 Ongoing Research

On the basis of this survey, it appears that studies on the geochemical issues associated with the use of paste backfill are primarily being conducted by consultants for individual mines. This is particularly true for newly proposed mines where the level of information required for water quality predictions and environmental impact assessments is increasing.

In addition to studies on individual mines, centers focusing on research of paste backfill geochemistry include:

- Université du Québec en Abitibi-Témiscamingue, Unité de recherche et de service en technologie minérale (UQAT-URSTM), Rouyn-Noranda – primarily civil engineering aspects (strength) and mineralogical/geochemical influences in terms of how geochemistry affects long-term strength (Benzaazoua et al. 1999, 2002, 2004 a,b,c). More recent laboratory studies also focused on the environmental problems such as metal leachability and water quality impacts from cemented paste backfill (Benzaazoua et al., 2006; Ouellet et al., 2006).
- École Polytechnique, Montréal – geochemistry and closure consideration (i.e. Bulyanhulu surface paste, Theriault et al., 2003) as well as mechanical issues (i.e. the development of an integrated method for analyzing the stability of backfilled stopes (Aubertin, et al., 2005).
- CANMET (Mining and Mineral Sciences Laboratories (MMSL)) – chemical stability of tailings backfill (Kwong, 2004).
- U.S. Environmental Protection Agency (USEPA) – Consideration of the potential impacts to drinking water from injection of mixtures of water, sand, mill tailings, or other materials into mined out portions of underground mines through mine backfill wells in limited studies associated with the Underground Injection Control (UIC) Program (promulgated in 1981).

Numerous other facilities, such as the University of Toronto, study the physical properties of backfill materials (DeSouza et al., 2003; Archibald et al., 1999) as well as the design of paste and thickened tailings applications, including cemented paste backfill, for underground mining (Le Roux et al., 2002a,b).

5.0 CASE STUDIES

Individual case studies of note are described in some detail below.

5.1 Crandon Mine, Wisconsin

Case study summarized from SRK (2000), Sollner et al. (2001) and Chapman et al. (2003).

The Crandon Project was a proposed mine project located in northeastern Wisconsin near the city of Crandon. Nicolet Minerals Company proposed to develop the project as an underground mine to remove approximately 50 million tonnes of ore from the massive

sulphide zinc-copper deposit. The project is no longer contemplated. The mining plan called for ore to be processed by conventional milling to produce zinc, copper and lead concentrates. Potentially acid-generating pyrite would be separated by flotation from the mine tailings into a pyrite concentrate. The pyrite tailings concentrate would be amended with 5%, by weight, Portland Cement (LaFarge Type 10) to form a cemented pyritic paste to backfill mined-out stopes and the de-pyritized tailings would be deposited in a surface storage facility. Overall, approximately 60% of the total tailings would be used as cemented pyritic paste backfill for the underground mine and 40% of the tailings (de-pyritized tailings) would be stored at the surface facility.

Upon mine closure, the underground mine workings would be allowed to flood and the water table was predicted to recover to within several feet of its pre-mine condition within four years. However, pyrite tailings that were returned underground early in the mine life could be accessible to air for an extended period of time (up to 30 years), allowing sulphide minerals to oxidize and thereby releasing stored oxidation products into the mine ground water as the water table recovered. SRK Consulting Inc. (SRK) predicted the water quality in the pyritic paste backfill pore space in the flooded mine using results from an extensive geochemical characterization program of the pyritic paste backfill, details of the proposed mine plan, and conservative assumptions.

The general approach taken by SRK to predict potential solute concentrations in the pyritic paste backfill upon mine flooding were as follows (Hockley et al., 1998; SRK Consulting, 2000):

- Thorough geochemical and mineralogical characterization of pyritic paste backfill (cemented) and pyrite concentrate (uncemented).
- Evaluate mining and backfilling methods in order to determine potential oxidation sites and oxygen transport processes within the pyritic paste backfill prior to flooding.
- Develop simple oxygen transport models, with conservative assumptions, to estimate the rate of oxygen supply to the pyritic paste backfill.
- Estimate the volume of cemented pyritic paste backfill that would be 'acidic' (long oxygen exposure), 'oxidized-neutral' (oxygen exposure for a short period of time) and 'unoxidized' (no oxygen exposure) based on the degree of backfill oxidation varying within a typical stope due to oxygen transport estimates, stope geometry, the mine plan and the availability of NP in comparison to oxygen limited oxidation rates.

- Estimate solute loads for each 'component' of paste backfill using contaminant release rates from kinetic tests (column tests) conducted on the pyritic paste backfill and the pyrite concentrate.
- Estimate contaminant concentrations using the estimated potential loads divided by ground water flow volumes.
- Check the estimated concentrations for solubility constraints using MINTEQA2.

The extensive characterization program on cemented pyritic paste backfill and uncemented pyrite concentrate included mineralogy, bulk chemical analyses, acid-base accounting, process water analyses, multiple batch and sequential leach tests, saturated column tests and humidity cell tests. Typical bulk chemistry and average NP values are shown in Table 8. Key results from static testing showed that (SRK Consulting, 2000):

- The uncemented pyrite concentrate had the potential to generate acid; however the proposed mining-backfilling methods would limit paste backfill oxygen exposure.
- The carbonate NP was strongly available, and did not include the significant additional NP contributed by oxide and hydroxide minerals resulting from cement addition to the cemented pyritic paste backfill.
- Cement content played the most significant role in determining how much NP was available to neutralize local oxidation.

Kinetic testing was conducted as part of the paste backfill characterization program to determine the effects of surface area on oxidation. SRK performed a series of column tests on molded cubes (1 cm) of cemented pyritic paste backfill (5% cement by weight). The cement amended tailings paste cubes were allowed to cure for 28 days prior to loading into the columns for testing. Each column test consisted of about 700 to 800 cubes. The columns tests were operated on a seven-day wet-dry cycle, with humidified air being passed through the columns for six days, and the columns being flushed on the seventh day with one litre of de-ionized water. Two of the three columns were operated for 20 weeks, and the third for 107 weeks. The results showed that (Chapman et al., 2003):

- The depth of oxidation in the cemented paste backfill was restricted to about 1 mm after 107 weeks of testing indicating oxygen entry into the cemented pyritic paste backfill was limited, likely by diffusion.
- Secondary minerals, such as gypsum and iron-oxy-hydroxides, formed a distinct 'rind' around the cubes that contributed to lower oxygen diffusion.

- Cement addition significantly contributed to acid neutralization by reducing the onset of acidic conditions in the cemented paste by more than one year (the pyritic tailings without cement produced acidic drainage in about 3 weeks).

The mining methods proposed at Crandon included blasthole open stoping below 300 feet and cut and fill above 300 feet. Once mined out, the stopes and cuts were to be backfilled with pyritic paste. Air-tight bulkheads and waste rock plugs were proposed to isolate backfilled stopes during operations thereby limiting oxygen transport to the stopes and limiting the extent of oxidation within the backfill. Therefore, SRK assumed only diffusive oxygen entry into the stopes during operations. SRK developed two oxygen transport models within the paste backfill for the prediction; a “Best Engineered Judgment” (BEJ) estimate which assumed that the oxidation rate limiting step was the oxygen diffusion rate into the backfill itself; and the “Upper Bound” (UB) estimate which assumed that the oxidation rate limiting step was the oxygen diffusion rate through the bulkhead and waste rock plug. The major difference between the two estimates was the assumed volume of acidic backfill.

The predicted solute concentrations associated with the cemented pyritic paste backfill components in the flooded Crandon Mine are summarized in Table 9. Overall, metals were predicted to be significantly elevated in the acidic backfill and sulphate was predicted to be significantly elevated in the acidic, unoxidized-neutral and unoxidized backfill.

Sensitivity analyses on the cemented pyritic paste backfill prediction calculations included the number of stopes, the exposed backfill surface area within each cross-cut, the exposure time, the pyritic paste backfill NP, and an early mine shutdown. The results indicated that the BEJ contaminant concentration estimates were insensitive to most changes (due to the large volume of unoxidized cemented paste backfill dominating the other sources) and that the UB estimates were sensitive to the input changes; in particular, those changes that affect the volume of acidic, cemented backfill. Sensitivity analyses showing the potential benefits of various source control measures indicated that oxygen barriers restricting oxygen access to the backfill and the direct removal of acidic backfill could achieve significant reductions in contaminant concentrations upon flooding.

In summary, the release of contaminant concentrations was shown to be limited by the rate at which oxygen could be transported into the cemented paste backfilled stopes. The water quality predictions performed by SRK at the Crandon Mine were an excellent example demonstrating the influence of cemented paste backfill geochemistry on mine water quality. Results from the pyritic paste backfill geochemical characterization were effectively utilized by conducting mine water quality predictions at closure. The prediction results, which indicated potential water quality issues with metals and sulphate upon flooding, signified the

need to plan and implement source control measures either during mine operations or at mine closure to avoid impacts to the surrounding ground water.

Unfortunately, it appears that the mine will not be constructed to allow field validation of the key assumptions and predicted values. The key assumption, that oxygen accessing the paste backfill can be limited to diffusion during operations by the construction of suitable bulkheads, requires field validation, perhaps at other sites that utilize or are planning to use similar bulkhead construction.

5.2 Snap Lake Diamond Project, Northwest Territories

Case study summarized from DeBeers, 2002.

The Snap Lake Diamond Project is a proposed underground diamond mine owned by DeBeers Canada Inc. (DeBeers) that is located on the western edge of Snap Lake, 220 km north and 52° east of Yellowknife, Northwest Territories. DeBeers proposes to mine approximately 22.8 Mt of kimberlite from a dyke which subcrops on the northwest peninsula of Snap Lake and dips below the lake. The kimberlite will be crushed and processed at an on-site facility with the fine processed kimberlite waste thickened to a paste. The paste will be amended with 1% to 2% cement, and used as cemented paste backfill in the underground mine workings. A portion of the coarse processed kimberlite (mostly tailings and grits less than 8 mm in size) will also be added to the paste. Uncemented paste will be pumped up to 2 km and stored on surface behind small berms.

Mineralogic analyses of the kimberlite indicated that the kimberlite is highly altered (no olivines were detected, the main constituent of 'fresh' kimberlite). The kimberlite mineral assemblage consists mainly of serpentine (lizardite) and dolomite, accompanied by lesser amounts of calcite. The smectite and sulphide content of the kimberlite is low. The principal sulphide minerals are pyrite and chalcopyrite. Other sulphides identified include pyrrotite, millerite, siegenite, and possibly violarite.

DeBeers' geochemical characterization program for the paste included an ABA analysis as well as short-term and sequential leach extraction tests. An ABA analysis was performed on one uncemented processed kimberlite sample. Three short-term leach extraction tests were performed on cemented paste backfill material to determine the readily-soluble constituents. Sequential leach extraction tests were conducted on cemented paste backfill (processed kimberlite with 1% to 2% cement) to identify solubility controls (Type I) and long-term leachability (Type II).

Although additional analyses were conducted on unthickened, uncemented processed kimberlite, direct comparison of changes attributable to cement addition and thickening could not be made due to the use of inconsistent test samples and/or analyses.

Selected test results for the acid-base accounting and leach tests on the paste backfill are shown in Table 10 and Table 11, respectively. Overall, the results indicated that the cemented paste backfill would generate alkalinity and a limited number of elevated metals (aluminum, copper, and possibly molybdenum and ammonium) (DeBeers, 2002).

DeBeers assumed that cured cemented paste backfill would act as a hydraulic barrier to ground water flow due to the formation of more stable minerals within the paste. These stable minerals would limit water infiltration into the paste backfill and therefore would limit the interaction between the paste backfill and mine water seepage. Thus diffusion-controlled exchange of chemicals was considered the main mechanism for the paste to influence the mine water quality. However, DeBeers did not directly use the cemented paste backfill laboratory results to predict mine water quality. The potential effects of cement addition on mine water quality was estimated from actual mine water monitoring data collected during the advanced exploration program where cement grout was used to limit ground water ingress into the mine. This was considered to be a conservative representation of potential water quality impacts from cement use at the proposed mine, in that cement loss during advanced exploration was quite high, and the major concern was total dissolved solids levels in the mine water. Acid generating and metal leaching potential of the kimberlite tailings portion of the paste and the majority of the mine wall were demonstrated to be low.

5.3 Unnamed Mine

Case study summarized from Verburg et al. (2000).

Golder Associates Inc. conducted a kinetic testing study on cemented paste tailings from an unnamed mine to determine the environmental stability of the paste tailings under both subaqueous and subaerial, (Verburg et al., 2000). These conditions were used to evaluate potential issues for flooded underground paste tailings backfill and surface deposition of paste tailings. The unnamed mine is a proposed copper mine with a volcanogenic massive sulphide orebody overlain by a gold-bearing gossan.

A geochemical characterization program was conducted on cemented paste tailings samples under both subaqueous and subaerial conditions, using both intact paste cylinders and crushed paste (crushed to <1 cm). The paste material consisted of washed pressure-leach residue tailings (approximately 55% finer than 20 µm material) containing between 33 and 36 wt% pyrite as sulphide sulphur, mixed with 5 wt% Ordinary Portland Cement (OPC) and

cured for a minimum of 28 days. A total of four paste tailings samples were tested and labeled as exposed intact paste, submerged intact paste, exposed crushed paste and submerged crushed paste. Thirty weeks of kinetic testing was conducted in test cylinders with the exposed paste tests operated according to conventional humidity cell testing procedures. The submerged paste tests operated in humidity cells with near-anoxic conditions.

The results of the pre- and post- kinetic test analyses conducted on the cemented paste tailings samples are shown in Table 12. The average weekly mass-based release rates and average weekly leachate concentrations from kinetic testing are presented in Table 13.

Results indicate that all four cemented tailings paste samples were reactive; however the paste reactivity varied according to the test conditions. The formation of ARD under subaerial conditions was almost instantaneous despite some alkalinity provided by the cement. Under submerged conditions, the generation of ARD was inhibited. Therefore, concentrations of sulphate, total iron, ferrous iron, and trace metals were higher under subaerial conditions than subaqueous conditions. Preferential leaching of neutralizing minerals from the cement occurred under both subaerial and submerged conditions

The observed sulphate trend in the submerged cells was considered likely due to the dissolution of gypsum, not pyrite oxidation, as calcium and sulphate were released in approximately equimolar quantities. The generation of equimolar quantities of sulphate and calcium through pyrite oxidation and dissolution of cement-forming minerals was considered unlikely, nor was the released calcium considered likely to have been provided by calcite due to over saturation at alkaline pH.

5.4 Louvicourt Mine, Quebec

The Louvicourt Mine, operated by Aur Resources Inc., is located in northwestern Quebec, about 600 km north of Montreal and 25 km east of Val D'or. The mine commenced underground production in 1994 on its volcanogenic massive sulphide deposit hosted in volcanic and sedimentary rocks. Copper, zinc, gold and silver are the target metals.

A paste backfill operation has functioned successfully for more than six years at the Louvicourt Mine (Cayouette, 2003a and b). Approximately 55% of thickened tailings from Louvicourt's 4300 tonne per day mill are fed to the 3500 tonne per day paste backfill plant to form a paste for underground backfill, with the remainder of the tailings pumped to the tailings pond. The paste, containing 2 to 4.5% binders in a mixture of 80% ferrous slag to 20% cement (Portland cement type 10), is piped underground to provide stability for

openings and support for pillar recovery. The paste backfilled stopes are barricaded with waste rock and shotcrete.

The Louvicourt Mine (Cayouette, pers. comm.) has indicated that a study on backfill geochemistry was conducted in 1996 by the Université du Québec en Abitibi-Témiscamingue, Unité de recherche et de service en technologie minérale (UQAT-URSTM) in Rouyn Noranda. Talings and binder formulations used by Bertrand (1998) were similar to those used by Louvicourt (V. Bertrand, pers communication). This geochemical information was not used in the prediction of short or long-term mine water quality. The mine does not routinely collect mine water samples percolating from paste backfilled stopes or other data that might be useful in evaluating the effects of paste backfill over time. It should be noted that the process water from the paste backfill plant contains no significant metal concentrations and the highest sulphate concentration in the process water has been 1200 ppm. The long-term strength of the Louvicourt paste backfill was determined to be stable after five years.

5.5 Eskay Creek Mine, British Columbia

The Eskay Creek Mine is a gold and silver mine located within the Unuk River watershed approximately 80 km north of Stewart, B.C. The underground mine has been in operation since 1995. The majority of the mined ore was crushed, blended and sold directly to smelters, although this ceased in 2005. A portion of the mined ore has been processed on-site in a gravity and flotation mill constructed in 1997 to produce concentrates, which are also shipped off-site for processing. The mine produced a maximum of approximately 600 tonnes of ore per day (Barrick, 2002), which has subsequently been reduced to less than 300 tonnes per day when direct shipping of ore ceased in 2003. The mine is backfilled with inert river gravel mixed with 4 to 8% cement by weight.

Prediction of underground mine water quality at closure was undertaken by Mehling Environmental Management Inc. assuming partial flooding of the mine workings. The prediction was based on kinetic tests conducted on the six defined waste rock types and ore samples (Higgs & Associates, 1993; Higgs et al., 1997), using methodology similar to MINEWALL (Morin, 1990). The prediction assumed that all wall rock surfaces had free access to unlimited oxygen during the mine life, including the wall rock surfaces in backfilled stopes. The prediction assumed that the main influence of the lean concrete backfill on mine water quality was the provision of alkalinity similar to that measured from drainage measured underground from freshly backfilled (pH = 13) and aged (pH 9, alkalinity of 200 mgCaCO₃/L) stopes.

While this case study does not include the use of paste backfill, it is of interest in that the assumptions for oxygen availability in the underground workings were based on actual measurements in unflooded workings. In 2002, four gas monitoring stations were established in the upper underground workings to resolve the question of oxygen availability to the backfilled stope walls. Figure 3 shows the type of instrumentation placed in the drillholes that intersected a partially isolated backfilled stope. Packers provided separate data for a section of intact backfill (backfill only), the contact between the backfill and the hanging wall, the contact between the backfill and the footwall, and a section that encompassed the entire width of the backfill, including the hanging and footwall contacts. The results (Table 14) indicate that the oxygen concentration was slightly less than atmospheric (ranging from 17.9 to 20.6%), possibly a result of oxidation of the sulphides in the wall rock and the tortuous path between the tested site and ventilated workings. However, the reductions in oxygen concentrations were considered unlikely to significantly reduce sulphide oxidation rates in the wall rock (or backfill if the backfill had contained sulphide minerals).

6.0 CONCLUSIONS AND RECOMMENDATIONS

The amount of available information and research on the influence of underground paste backfill on mine water quality is typical of a relatively new field. Research by the community at large to date has generally focused on the structural characteristics of paste in terms of meeting the required backfill strength using the most economic amount and mix of binder materials. Cemented paste backfill research tends to focus on strength and mining aspects, and little on the environmental implications. In light of the belief that the chemical reactivity of tailings and the volume of leachate generated are reduced by thickening, and by the addition of alkaline additives such as cement, little information on the influence of paste backfill on mine water quality appears to have been developed. Exceptions have been where the mineralogy and reactivity are extreme with potential effects on paste strength (Bernier and Li, 2003), or where a portion of the paste is being deposited on surface with potential surface water impacts. Some research in this field has also been initiated in the United States as a result of the Underground Injection Control Program (UIC, promulgated in 1981 by the U.S. Environmental Protection Agency) that includes placement of mine waste backfill in underground mines under its legislation (Levens et al., 1996). Recognition of the fact that any backfill has the potential to generate contaminant plumes in the long-term, and potentially influence ground and/or surface water appears to have increased the site-specific evaluation of paste characteristics of newly proposed mines in recent years.

Information on the geochemistry of paste backfill was found to focus predominantly on the geochemical characteristics of paste backfill mixes (i.e. at the laboratory or micro level), with some general discussions on how the paste would act in the mine environment. Studies often looked at fresh paste in a submerged, potentially acidic environment, and seldom consider how much oxidation might occur during operations before the mine workings became flooded, i.e. how many soluble products would be available for release at closure. The studies did not attempt to separate out the geochemical influence of thickening versus binder addition, as most studies examined the materials only in the form that they would be utilized. Studies evaluating materials with or without cement typically noted the significant effects of cement addition on short-term geochemistry and associated water quality. Cement addition had less significance where the tailings were extremely reactive. In general, as noted by Levens et al. (1996), the overall impact of cemented backfill is expected to be less than the impact from uncemented fill. Thus comparative data between similar materials with and without cement or other binders is usually missing.

Few examples were available which used paste characterization data from the laboratory to quantitatively predict mine water quality. For example, there may exist detailed laboratory assessment of dissolution chemistry, with a general description of adverse consequences to paste backfill surfaces, but few quantitative links to potential long-term leachate quality at the full mining scale. The focus on smaller scale aspects of the problem (i.e. paste characteristics and effects of cement chemistry) is not unusual for a relatively new field.

Most studies to date have been based on relatively established laboratory tests developed for acidic drainage and metal leaching assessment of mine wastes in general (i.e. static and kinetic tests and others as described in MEND Manual, 2001; MEND, 1989, 1991a, 1991b, 1994a, 1994b, 1995a, 1995b, 1996, 1997; Price, 1997), with some modifications to address the more cohesive nature of paste, particularly pastes with added binders.

While general theories describing how paste backfill would react in an underground environment appeared sound, these are limited by a lack of field verification. The next step requires application of laboratory test results to actual underground depositional environments, encompassing the common issues associated with the scale-up of laboratory results.

One of the difficulties in developing field verifications of laboratory based predictions is the numerous aspects that may influence the results in an underground environment in an active mine: changing ground water flow and quality, influences of new backfill in adjacent stopes, drill water and water from muck stations, ventilation patterns. These difficulties in a real mine environment may mean that the next step will require more controlled conditions, such as an

isolated stope that is backfilled with paste so that the trends in mine water quality can be defined over time.

Another aspect that requires field validation is the reported benefits of thickened over unthickened (paste) tailings. The main benefits of thickened tailings (higher density, higher degree of saturation, and therefore less sulphide oxidation) appear to have been assessed or compared on a laboratory scale over relatively short periods of time. Comparison of thickened and unthickened tailings attributes at larger field scales (i.e. relative depth of reactions, soluble loads produced, and exposed surface areas) is required to clarify the potential extent of the projected benefits from thickened tailings.

At the field scale, there also appears to be a lack of cohesiveness between the various theories being applied to this issue. For example, flow through backfill is compared to that of fractured porous media (Levens et al., 1996), which has a solid analytical basis. This appears to be a valid comparison for saturated or flooded scenarios, particularly as chemical reactions in backfill appear to be predominantly surface phenomenon. However, paste geochemistry data from laboratory tests are often used as mass generated loads, instead of contaminant loads created from surface reactions. Often, the various approaches that have been used to address individual aspects of a site prediction (i.e. hydrology and geochemistry) do not appear to have been linked to provide a comprehensive, coherent "big" picture of what may be transpiring.

Most studies and/or recent discussions emphasize that it is critical to consider the contaminant producing potential of the specific paste backfill being used in the long-term, under the site-specific operational storage conditions and proposed closure.

6.1 Key Parameters and Information Gaps

Predictions attempted to date suggest that the key parameters that may influence reactivity of paste backfill are:

- Tailings geochemistry (sulphide content and reactivity);
- Binder content and geochemistry;
- Oxygen availability, and diffusion into paste;
- Paste strength development and loss (and subsequent enhancement of water and oxygen access).

The general questions to be answered are:

- How does thickening the tailings to a paste alter its geochemical reactivity?

- How does the addition of binders, such as cement, influence the paste's reactivity and resulting leachate products?
- How do the conditions in the underground environment influence reactivity of the paste?

The ability to assess tailings and cemented paste geochemistry in a laboratory environment appear to be sufficient to address paste backfill. Therefore the areas that could apparently benefit from further examination and/or field validation tend to focus on specific binder/aggregate interactions and in-situ conditions. Carlson (pers. communication, 2004) notes that generally an improved understanding of hydraulic conductivity, porewater chemistry and compressive strength is need for paste backfill.

Thus possible areas for further study are:

Thickened Tailings Benefits

Large scale thickened versus non-thickened tailings tests to assess the proportion of the deposit that benefits from increased density and/or increased degree of saturation.

Binder Content and Chemistry

A number of issues relate to binder content and chemistry, particularly cement chemistry that are unique in terms of ARD and metal leaching predictions. These include:

- Rate of loss of cement NP
- Mechanism of NP depletion (loss due to flushing versus acid neutralization);
- Binder hydration reactions (effects of paste water content on hydrated binder chemistry and mineralogy);
- Rate and degree of curing in-situ (i.e. underground);
- In-situ strength development and loss; and,
- Addition of relevant cement chemical equations to the thermodynamic databases used in geochemical equilibrium analyses.

These might be addressed by adding experts in cement chemistry to the multidisciplinary field of ARD research, and/or by focused studies on cement chemistry.

As suggested by Levens et al., 1996, factors relevant to the contamination potential of cemented backfill that warrant further study include:

- The relationship between residual saturation of backfill and the addition of cement;

- The reduction in sulphide oxidation and buffering resulting from armoring of preferential flow paths;
- Changes in the strength of cemented backfill in the long term caused by sulphide oxidation; and,
- The quality of residual pore water after backfilling.

These might be assessed by a combination of focused laboratory tests and monitoring and examination of backfilled materials. Drill-extracted samples of intact backfill and backfill surfaces could be examined at various stages over the mine operational and closed period.

Paste Breakdown

Geochemical factors control the breakdown of paste backfill over time, including:

- ARD/sulphide oxidation mechanisms within backfill;
- Mechanisms of leaching and weathering; and
- Characteristics of ARD/leaching by-products.

These have significance with respect to reductions in backfill strength, but should also be considered in terms of the potential to increase reactive surface area. The potential to increase reactive surface areas would be a natural extension of current research into geochemical factors influencing long-term paste backfill strength.

Underground Mine Environment

Understanding the availability of oxygen in various underground environments:

- Oxygen entry into paste mass (i.e. Is it limited to diffusion during operations and after closure?);
- Oxygen availability at stope and mine scales at the backfill surfaces under various conditions (i.e. backfilled stopes in operating mines, backfilled stopes in closed unflooded mines);
- Results of paste deterioration on permeability and porosity; and,
- Effects of paste backfill breakdown on ground water flow paths through and/or around backfilled stopes.

These might be addressed through detailed monitoring of paste surfaces boundaries and the intact paste backfill, similar to that undertaken at Eskay Creek Mine.

Means to assess the range in available reactive surfaces:

- To what degree are air accessible surfaces introduced in paste backfilled stopes?
- How significant are wall gaps and gaps between successive backfill campaigns?
- How completely might stopes be backfilled on average?

This might be addressed through drilling of existing stopes.

Scale-up Issues /Combined Influences

- In-situ backfill weathering characteristics;
- Assessment of stope water quality evolution;
- Assessment of pore water quality evolution within the backfill mass; and,
- Monitoring of chemical and physical behaviour of backfill under operational conditions.

These might be addressed through instrumentation and monitoring of placed paste backfill in operating mines over an extended period of time. As noted above, monitoring under controlled conditions, such as an isolated stope, would assist in separating the various influences on scale-up, as most mines have complex environments and changing conditions.

Case Studies

The long timeline associated with verification of predictions associated with ARD, particularly under conditions designed to reduce reactivity, such as placement underground as paste backfill, necessitates that detailed information be collected from numerous sites over long periods of time. Detailed laboratory characterization data, placement methods and success, in-situ paste characterization, characterization of in-situ conditions, and monitoring of the resultant water quality during operations and after closure, should be collected in order to verify assumptions, and correlate predictions with actual results. Reports of failures are just as important to ensure that other operations do not repeat the same errors or omissions.

Terminology

At a more basic level, as with most new fields, the terminology in use appears to be inconsistent and would benefit from standardized definitions. For example, referral to 'paste backfill' sometimes assumes the presence of binders such as cement, and at other times appears to refer simply to the flow characteristics of the material – with or without binder addition. Terms that are in the literature include: thickened tailings, tailings backfill, dense

tailings, sandfill, cemented paste tailings, cemented paste backfill, paste backfill and paste tailings. The lines also blur with the introduction of coarser materials, leading to terms such as cemented mine waste backfill.

6.2 Summary

In summary, the use of paste backfill in underground environments has been generally considered beneficial to reduce overall environmental impacts associated with mining. The general theories associated with paste backfill characteristics and geochemical reactivity appear sound, but there does not appear to be much field validation of actual influence of key parameters. Lack of controlled conditions in active mine environments appears to significantly limit the ability to separately assess potential scale up issues. The field would benefit from research targeted at the specific components of paste theory (such as the separation of the influence of thickening and binder addition (e.g. ongoing work being conducted by UQAT-URSTM, Rouyn-Noranda, and Ecole Polytechnique, Montreal), examination of scale-up issues (preferably in the controlled environment of an isolated well characterized and instrumented backfilled stope), collection of detailed case studies, and additional monitoring of mine waters to assess the influence of paste backfill on mine water quality over time.

In the bigger picture, there may be a need to better define the potential importance of this issue, such that priorities for studying this matter can be assessed. For example, by determining whether existing backfilled mines produce significant ground water contaminant plumes. Certainly sidehill mines that continue to drain from portals or other openings are known to be potential closure problems when not suitably mitigated (i.e. Britannia Mine in B.C.; Summitville in Colorado). And there appears to be sufficient information to suggest that there might be potential impacts from backfilled mines where the wall rock and backfill are particularly reactive (i.e. Bernier and Li, 2003). However, a general survey of existing underground mines might put the significance of the issue in perspective.

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TABLES

Table 1: Mine A Fresh and Oxidized Pastes ABA

(from Bernier and Li, 2003)

Mine A	MA-F	MA-Y	MA-R
Sample	Fresh paste	Yellow paste	Red paste
Paste pH	7.91	2.93	2.33
Fe sulphides	11.81	6.50	4.08
S total	14.00	12.40	11.90
SO ₄	1.02	14.45	21.40
CO ₂	5.32	1.21	0.29
S ²⁻	13.66	7.58	4.77
SAP	426.88	236.98	148.96
CNP	120.64	27.44	6.58
CNNP	-306.24	-209.54	-142.38
CNP/SAP	0.28	0.12	0.04
Minerals	Quartz, chlorite, albite, pyrite, ankerite, minor siderite, pyrrhotite, chalcopyrite, sphalerite, ilmenite, magnetite		

Notes:

SAP = Sulphides Acid Potential

CNP = Carbonate Neutralization Potential

CNNP = Carbonate Net Neutralization Potential

Expressed in kg CaCO₃ equivalent per tonne of sample

Table 2: Mine B Tailings and Oxidized Pastes ABA

(from Bernier and Li, 2003)

Mine B	MB-tails	MB-G	MB-R
Sample	Filter Cake	Green paste	Red paste
Paste pH	8.09	5.58	4.16
Fe sulphides	11.04	6.11	1.63
S total	17.99	13.10	12.71
SO ₄	0.90	8.12	17.73
CO ₂	8.31	4.64	0.41
S ²⁻	13.57	7.56	2.52
SAP	424.06	236.25	78.75
CNP	188.44	105.22	9.30
CNNP	-235.62	-131.03	-69.45
CNP/SAP	0.44	0.45	0.12
Minerals	Quartz, chlorite, talc, sepiolite, pyrite, calcite, ankerite, magnetite, pyrrhotite	Nearly complete depletion of carbonates and pyrrhotite, appearance of gypsum, goethite, anhydrite, hematite	

Notes:

SAP = Sulphides Acid Potential

CNP = Carbonate Neutralization Potential

CNNP = Carbonate Net Neutralization Potential

Expressed in kg CaCO₃ equivalent per tonne of sample

Table 3: Mine C Oxidized Pastes ABA

(from Bernier and Li, 2003)

Mine C	MC-A	MC-B	MC-RL
Sample	Hot paste not glowing	Hot paste glowing	Red lump in ore pass
Paste pH	9.35	3.65	2.13
Fe sulphides	28.17	21.50	2.76
S total	31.80	29.40	11.60
SO ₄	1.14	14.30	22.40
CO ₂	5.23	1.53	0.77
S ²⁻	31.40	24.60	4.12
SAP	981.25	768.75	128.75
CNP	118.59	34.62	17.56
CNNP	-862.66	-734.13	-111.19
CNP/SAP	0.12	0.045	0.14
Minerals	Quartz, chlorite, pyrite, calcite, ankerite, gypsum, pyrrhotite	Mineralogy between MC-A and MC-RL	Nearly complete depletion of carbonates, pyrrhotite, appearance of anhydrite, hematite

Notes:

SAP = Sulphides Acid Potential

CNP = Carbonate Neutralization Potential

CNNP = Carbonate Net Neutralization Potential

Expressed in kg CaCO₃ equivalent per tonne of sample

Table 4: Chemical Composition of Ordinary Portland Cement⁽¹⁾

(from Bertrand, 1998)

Principal components of dry cement	Typical Portion	Principal hydration products	Function
Tricalcium silicate: C ₃ S Ca ₃ SiO ₅ (alite) Rapid hardening, early strength development	~50%	1) $2C_3S + 6H_2O \rightarrow Ca_3Si_2O_7 \cdot 3H_2O^{(a)} + 3Ca(OH)_2^{(b)}$ 70% reacted in 28 days	a) Tobermorite gel: principal binding agent of cement. b) Portlandite: no cementing properties
Dicalcium silicate: C ₂ S Ca ₂ SiO ₄ (belite) Slow hardening, later stage strength development (after one week).	~25%	2) $2C_2S + 4H_2O \rightarrow Ca_3Si_2O_7 \cdot 3H_2O^{(a)} + Ca(OH)_2^{(b)}$ 30% reacted in 28 days; 90% in one year	Same as above
Tricalcium aluminate: C ₃ A Ca ₃ Al ₂ O ₆ Consumes Ca(OH) ₂ , produces a high heat of hydration.	~10%	3) $C_3A + 12H_2O + Ca(OH)_2 \rightarrow Ca_4Al_2O_6(OH)_2 \cdot 12H_2O^{(c)}$ 4) $C_3A + 10 H_2O + CaSO_4 \cdot 2H_2O \rightarrow Ca_4Al_2(SO_4) \cdot 12H_2O^{(d)}$ 5) $C_3A + 26H_2O + 3CaSO_4 \cdot 2H_2O \rightarrow Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O^{(e)}$	c) Tetraclacium aluminate hydrate: some early strength development d) Monosulfoaluminate and e) Ettringite: expansive minerals produced from the reaction of dissolved gypsum with C ₃ A
Tetracalcium aluminoferrite: C ₄ AF Ca ₄ Al ₂ Fe ₂ O ₁₀ Manufacturing purpose to reduce clinkering temperature; responsible for colour effects in cement.	~8%	6) $C_4AF + 50H_2O + 2 Ca(OH)_2 \rightarrow Ca_6Al_2Fe_2O_{14} \cdot 12H_2O^{(f)}$ 7) $C_4AF + 12H_2O + 6CaSO_4 \cdot 2H_2O + Ca(OH)_2 \rightarrow Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O^{(e)}$	f) Calcium aluminoferrite hydrate: rapid hydration but little strength contribution. Slow hydration reaction to produce ettringite.
Gypsum: C \underline{S} H ₂ CaSO ₄ ·2H ₂ O Very rapid dissolution, slows the rate of C ₃ A hydration to avoid flash setting.	~5%	Dissolved gypsum may participate in reactions (4), (5), (6) and (7), depending on the local pore water chemistry.	Too much gypsum may favour the formation of ettringite over portlandite.
Fe, K, Mg Present in clays used to make Portland cement.	Few %		May be included in any cement phase in solid solution.

Notes:

This table is adapted from Kosmatka 1995 and Taylor 1997.

¹⁾ Ordinary or Normal Portland Cement = Canada Type 10 or Mexico No. 1.

Tricalcium silicate hydrate or "tobermorite gel": composition may vary and include trace concentrations of Fe, Mg, K. The cement industry uses abbreviated nomenclature for the unhydrated cement components such that the oxide in the minerals phases is referred to be one letter: C = CaO, S = SiO₂, A = Al₂O₃, F = Fe₂O₃, \underline{S} = SO₄, H=H₂O. In the cement literature, the alite phase of cement is written C₃S, referring to the composition: 3CaO·SiO₂, or, in analytical chemistry, Ca₃SiO₅. This terminology is used in this table to permit correlation with the cement literature.

Table 5: Concrete Subjected to Sulphate Attack

(from Bertrand 1998)

Degree of Exposure	Water soluble sulphate in soil sample (%)	Dissolved sulphate in contact with concrete (g/L)	Portland cement type to be used
Very severe	>2.0	>10.0	50
Severe	0.2 – 2.0	1.5 – 10.0	50
Moderate	0.1 – 0.2	0.15 – 1.5	20, 40 or 50

Adapted from Kosmatka et al., 1995

Table 6: Replacement Components of Portland Cement to Improve Sulphate Resistance of Concrete

(from Bertrand, 1998)

Additive	Effect
Fly ash: Coal combustion residue; low calcium (Torri et al., 1995) (Djuric et al., 1996)	Lower air and pore volume, reduced permeability, increases resistance to sulphate absorption into concrete
Silica fumes: Silicon, silicon alloy smelting ash residue; minimum 75% silicon, very low calcium and aluminium oxides (Aköz et al., 1995)	Lower air and pore volume, very reduced permeability, decreases gypsum and ettringite formation, increases electrical resistivity (corrosion protection)
Blast furnace slag: Glassy iron smelting residue; calcium silicates and aluminosilicates may be high (13 – 15%) Al ₂ O ₃ slag or low (3 – 5%) Al ₂ O ₃ slag (Irassar et al., 1996)	Lower air and pore volume, reduced permeability, may increase mixture strength in the end

Table 7: Paste Backfill Survey Results

	Mine	Company	Location	Status	Type	Binder	Binder Concentration	Paste/Backfill Geochem. Info	Minewater Prediction?	Longterm Strength?	Backfill Perculation?	Mine Waters as a Whole?	Contact	Notes	
Underground	Canada														
	Snap Lake	DeBeers	NWT	proposed	Paste	100% cement	1% - 2%	y	y	?	n	n	Snap Lake EIA	Mine water quality from advance exploration grouting used a an analog	
	Louvicourt	Aur Resources	Val d'Or, QC	operating	Paste	80:20 slag:cement	2% - 4.5%	y	n	y	n	n	Daniel Talbot, Louis Racine, Aur Resources		
	Langlois	Breakwater	Clericy, QC	operating	Paste	100% cement	3% - 6.5%	n	n	n	n	n	Bob Careau, Breakwater	Info from Lucienne Anctil, Breakwater_Bouchard, Ebert	
	Bouchard-Hebert	Breakwater	Clericy, QC	operating	Paste	50:50 fly ash:cement	2% - 5%	n	n	n	n	n	Bob Careau, Breakwater		
	Doyon	Cambior	Rouyn-Noranda, QC		Paste	100% cement	2.1%	y	n	y	n	n	Suzie Belanger, Serge Vezina, Cambior		
	Red Lake	Goldcorp	Balmertown, ON	operating	Paste				n			y	Randy Wepruk, Goldcorp		
	Lupin Mine	Kinross	Lupin, NU	closing	Paste	100% cement	2%	?	n				Mike Tansy, Kinross	paper, CIM conf Edmonton 1996	
	Garson	Inco	Copper Cliff, ON		Paste	100% cement	3%	n	n				Greg Puro, Inco		
	Golden Giant	Newmont	Hemlo, ON	operating	Paste	50:50 fly ash:cement	5%	y	y	y	n	y	Wally Senza, Newmont	Initial testing conducted, but a dry mine so that collected mine waters are introduced.	
	Brunswick	Noranda	Bathurst, NB		Paste	100% cement	2% - 5%						Bob Butler, Noranda		
	Matagami	Noranda	Macadamia, QC		Paste	100% cement							Bob Butler, Noranda		
	Myra Falls	Breakwater	Campbell River, BC	operating	Paste									Recent conversion from sandfill to paste	
	USA														
	Crandon	NWRG	Crandon, Wisconsin	proposed	Paste	100% cement	5%	y	y	?d	n	n	Kelly Sexsmith/Darryl Hockley SRK	Paste made from pyritic concentrate	
	Stillwater	Stillwater	Nye, Montana	operating	Paste									No contact	
	Silver Strand	New Jersey	Idaho	planned	Paste			y	y	n	y	y	Fred Brackenbusch, CEO, New Jersey Mining Co.	Small mine, still in conceptual planning stages.	
	Lucky Friday	Hecla	Idaho	operating	Paste									Mike Dexter, Hecla	
	Greens Creek	Kennecott, RTZ	Alaska	operating	Paste									Fred Brackenbusch -->	
	Big Island Mine	OCI	Green River, WY											Fred Brackenbusch -->	
	Elsewhere														
	Kimberley	BHP-Billiton	South Africa	operating										John Chapman, SRK; and SRK office, South Africa	No known info on kimberlite geochemistry
	Cannington	BHP-Billiton	Queensland, Aus												
Henty Gold	Placer Dome	Tasmania													
Bulyanhulu	Barrick	Tanzania, E. Africa	operating		Paste/crushed rock								Therault et al., 2003		
Cement/Aggregate	Eskay Mine	Barrick	Northwestern BC	operating	Lean Concrete	100t5 cement	4 - 8%	limited	y	y	y	y	Peri Mehling, MEMI	Use of clean aggregate with cement (4 - 8%)	

Table 7: Paste Backfill Survey Results (cont'd)

	Mine	Company	Location	Status	Type	Binder	Binder Concentration	Paste/Backfill Geochem. Info	Minewater Prediction?	Longterm Strength?	Backfill Percolation?	Mine Waters as a Whole?	Contact	Notes
Surface Applications	Canada													
	Snap Lake	DeBeers	NWT	proposed	Paste Tailings	none		y	y				Rens Venburg/Ken deVos, Golders	
	Myra Falls	Breakwater	BC, Canada	operating	Paste Tailings									Conversion to tailings paste storage in 2004
	USA													
	Pogo	Teck-Cominco	Fairbanks, Alaska	proposed	Paste Tailings			y	y				Steve Day, SRK	
	Rodeo-Miekle	Barrick	Carlin, Nevada	proposed	Paste Tailings									
	Silver Strand	New Jersey	Idaho	planned	Paste Tailings			y	y	n	y	y	Fred Brackenbusch, CEO, New Jersey Mining Co.	Small mine, still in conceptual planning stages.
	Crandon	NWRG	Crandon, Wisconsin	proposed	Paste Tailings			y	y	?	n	n	Chapman et al., 2003	De-pyritized tailings
	Colstrip	Peabody	Colstrip, Montana											
	Elsewhere													
Bulyanhulu	Barrick	Tanzania, E. Africa	operating	Paste Tailings	none									
Kubaka	Omolon Gold	Russia	operating	Paste Tailings	none					?			Literature source	
Cement/Waste Rock or Cement/Mill Tails	Canada													
	Bousquet	Barrick	Preissac, QC	closed	Rock Fill	50:50 fly ash:cement	4% - 7%	?	?	?	?	?	Vernon Betts, Barrick	Mine is close, no point of contact established.
	Holt-McDermott	Barrick	Kirkland Lake, QC		Rock Fill	60:40 fly ash:cement	5%	n	n	n	n	n	V. Betts and Ron Martel, Barrick, Eskay Creek	Not an acid water producing mine, therefore, very little geochemistry studied
	Doyon	Cambior	Rouyn-Noranda, QC		Rock Fill	50:50 fly ash:cement	2%						Suzie Belanger, Serge Vezina, Cambior	
	Lupin Mine	Kinross	Lupin, NU	closing	Dev. Waste	100% cement	2%	?	n				Mike Tansey, Kinross; Jim Cassie, BGC	paper, CIM conf Edmonton 1996
	Golden Giant	Newmont	Hemlo, ON		Rock Fill	50:50 fly ash:cement	4%						Wally Senza, Newmont	
	Holloway	Newmont	Matheson, ON		Rock Fill	60:40 fly ash:cement	3%						Wally Senza, Newmont	
	Birchtree	Inco	Thompson, MB		Rock Fill	70:30 fly ash:cement	3.5%	n	n	n	n	n	Ike Isagon, Inco	Only routinely measure pH at one location.
	Coleman/McCreedy East	Inco	Copper Cliff, ON		Mix	100% cement	10% max	n	n	n	n	n	Ike Isagon, Inco	Only routinely measure pH at one location.
	T-1	Inco	Thompson, MB		Mill Tails	100% cement	4%	n	n	n	n	n	Ike Isagon, Inco	Only routinely measure pH at one location.
	T-3 & 1-D	Inco	Thompson, MB		Mill Tails	100% cement	4%	n	n	n	n	n	Ike Isagon, Inco	Only routinely measure pH at one location.
	T-3 & 1-D	Inco	Thompson, MB		Waste Rock	50:50 fly ash:cement	4%	n	n	n	n	n	Ike Isagon, Inco	Only routinely measure pH at one location.
	Polaris	Teck-Cominco	Polaris, NU		Rock Fill	100% cement	4%	n	n	n	n	n	Janet Frieth, Teck-Cominco	Ore-body hosted in permafrost. All groundwater was essentially frozen.
	Williams/David Bell	Teck-Cominco	Hemlo, ON		Rock Fill	55:45 fly ash:cement	2%						Janet Frieth, Adele Faubert, Teck-Cominco	
	Myra Falls	Boliden	Campbell River, BC	operating	Rock Fill?			?	n					
	USA													
Rodeo-Miekle	Barrick	Carlin, Nevada	operating	Rock Fill	100% cement	5%	n	n	n	n	y	Lyndon Clark, Miekle-Rodeo	Dry mine but with acidic seeps	

Table 8: Summary of Bulk Chemistry and Average Neutralization Potentials

(from SRK, 2000)

Parameter	Units	Pyrite Concentrate Average	Pyritic Paste Backfill	Cement (La Farge Type 10)
Antimony	mg/kg	40	65.5	10
Arsenic	mg/kg	3,600	2,500	300
Barium	mg/kg	<20	20	360
Beryllium	mg/kg	<10	<20	<20
Cadmium	mg/kg	85	27.5	<5.0
Calcium	mg/kg	2,900	19,350	549,000
Chromium	mg/kg	92	185	55
Cobalt	mg/kg	83	100	12
Chloride	mg/kg	no data	no data	no data
Copper	mg/kg	995	1,000	46
Fluoride	mg/kg	no data	no data	no data
Iron (total)	mg/kg	376,000	-	14,400
Lead	mg/kg	4,200	3,750	<500
Magnesium	mg/kg	5,400	6,200	12,300
Manganese	mg/kg	340	265	320
Mercury	mg/kg	4.75	3.75	<0.3
Nickel	mg/kg	55.5	62.5	58
Selenium	mg/kg	105	95	<3
Silicon	mg/kg	52,850	56,050	-
Silver	mg/kg	29.5	25.85	<0.5
Strontium	mg/kg	7.85	26.5	300
Sulfur (T)	mg/kg	432,500	399,000	12,100
Zinc	mg/kg	12,100	10,900	500
Modified Sobek NP	kgCaCO ₃ eq./tonne	15.4 ¹	45.5	45 ²
CO ₃ -NP	mg/kg	-	23.5	-

Notes:

Cement (La Farge Type 10): The pyritic paste backfill contains approximately 5% cement (by weight).

Modified Sobek NP represents an average NP of six different samples (curing times = 28 and 90 days, respectively).

CO₃-NP represents an average NP of six different samples (curing times = 28 and 90 days, respectively); only 36% of the carbonate in the pyritic paste backfill is present as (Ca+Mg)CO₃-NP. Therefore not all the CO₃-NP is available for neutralization.

¹Average NP contribution from Pyrite Concentrate, NP contribution = NP (Pyrite Concentrate) * 0.95.

²Estimated by adding the NP contribution of cement (5% cement content, 30 kgCaCO₃/tonne to the NP of pyrite concentrate (15.4 kgCaCO₃/tonne).

Table 9: Predicted Solute Concentrations Associated with Cemented Pyritic Paste Backfill in the Reflooded Crandon Mine

(from SRK, 2000)

Parameter	Best Engineering Judgement (BEJ)				Upper Bound (UB)			
	Acidic	Oxidized/ Neutral	Unoxidized	Overall	Acidic	Oxidized/Neutral	Unoxidized	Overall
Pore vol. (ft ³)	6.02x10 ²	4.66x10 ⁵	2.12x10 ⁸	2.12x10 ⁸	1.66x10 ⁵	4.66x10 ⁵	2.12x10 ⁸	2.12x10 ⁸
Al mg/L	1,896	0.0015 *	0.025	0.030	1,896	13	0.025	1.5
Sb mg/L	2.1	0.033	0.0012	0.0013	2.1	0.33	0.0012	0.0036
As mg/L	650	0.24	0.0053	0.0076	650	1.1	0.0053	0.52
Ba mg/L	0.00071 *	0.0031 *	0.0057 *	0.0057	0.60	3.0	0.51	0.52
Be mg/L	0.082	0.0077	0.00033	0.00035	0.082	0.028	0.00033	0.00045
B mg/L	0.029	Nd	0.0054	0.0054	0.029	nd	0.0054	0.0054
Cd mg/L	26	0.0059	0.000065	0.00015	26	0.011	0.000065	0.02
Ca mg/L	471 *	587 *	954 *	953	2,602	716	980	981
Cl mg/L	251	251	251	251	251	251	1,900	1,895
Cr mg/L	21	0.095	0.000070	0.00034	21	0.17	0.000070	0.017
Co mg/L	18	0.040	0.084	0.084	18	0.10	0.084	0.098
Cu mg/L	760	0.22	0.0027	0.0053	760	0.58	0.0027	0.60
F mg/L	53	1.0 *	nd	0.0024	53	8.1	nd	0.060
Fe mg/L	59,756	0.29	0.0080 *	0.18	59,756	1.5	0.037	47
Pb mg/L	3.1	0.27	0.0024 *	0.0030	520	0.30	0.038	0.44
Mg mg/L	2,852	7.4	0.28	0.30	2,852	160	0.28	2.9
Mn mg/L	193	0.0053	0.0022	0.0028	193	0.086	0.0011	0.15
Hg mg/L	0.27	0.00060	0.000080	0.000082	0.27	0.0023	0.000080	0.00030
Ni mg/L	3.3	0.039	0.000072 *	0.00017	3.3	0.14	0.027	0.030
K mg/L	24	879	160	162	24	1,125	160	162
Se mg/L	7.1	0.51	0.031	0.032	7.1	1.6	0.031	0.040
Ag mg/L	0.021 *	0.021 *	0.00023	0.00028	0.37	0.71	0.00023	0.0021
Na mg/L	291	287	67	67	291	291	67	68
SO ₄ mg/L	164,173 *	2,147 *	1,250	1,252	169,555	2,659	1,317	1,451
SO ₄ from S ₂ O ₃ mg/L	686	686	686	686	1,371	1,371	1,371	1,371
Zn mg/L	9,322	0.54	0.042	0.070	9,322	1.1	0.042	7.3

Notes:

"nd" = no data

* - parameter solubility controlled

Table 10: Acid-Base Accounting of Processed Kimberlite Paste from Snap Lake

(from DeBeers, 2002)

Sample ID	200008
Paste pH	11.30
CO ₂ (wt %)	2.35
Total Sulphur (wt %)	0.12
Standard Sobek NP (kgCaCO ₃ /tonne)	221.4
CaNP (kgCaCO ₃ /tonne)	53.3
AP (kgCaCO ₃ /tonne)	2.5
Sulphate Sulphur (wt %)	0.04
Sulphide Sulphur (wt %)	0.08
NNP (kgCaCO ₃ /tonne)	218.9
NP:AP	88.6
CaNP:AP	21.3

Notes:

NP = Neutralization Potential

CaNP = Carbonate Neutralization Potential

AP = Acid Potential

NNP = Net Neutralization Potential

Table 11: Summary of Leach Test Results on Cemented Paste Backfill from Snap Lake

(from DeBeers, 2002)

Parameter	Unit	Type I ¹ (Fresh Solids)	Type II ² (Fresh Lixiviant)	A1 Leach ¹	Average of 3 SWEF Tests
pH	std. Units	11.8-12.2	11.4-11.9	11.8	11.9
Alkalinity	mg/L CaCO ₃	760-980	50-490	760	520
SO ₄	mg/L	2.7-5.3	13.2-43	5.34	8.14
Cl	mg/L	8.6-33	0.76-2.3	8.64	3.13
Total P	mg/L	0.01-0.09	<0.010	0.013	0.13
PO ₄	mg/L - P	-	-	-	-
NH ₃	mg/L - N	6.6-23	0.20-1.3	6.6	1.5
NO ₃	mg/L	0.53-1.0	0.26-0.37	0.53	2.14
Al	mg/L	0.47-0.59	0.60-0.66	0.47	0.59
As	ug/L	0.7-1.2	0.4-0.9	0.7	1.0
Cd	ug/L	<0.3-0.4	<0.05-0.1	<0.3	<1
Co	ug/L	<0.5-0.6	<0.1-0.2	<0.5	<2
Cr	ug/L	313-392	79.6-265	313	183
Cu	ug/L	5.1-16.8	0.9-4.6	5.1	18
Fe	mg/L	<0.01-0.01	<0.01	<0.01	<0.03
Hg	ug/L	<1	<1	<1	<1
K	mg/L	19.0-47.5	10.1-14.3	19.0	13.0
Mn	ug/L	<0.3-0.6	0.22-1.4	<0.3	<2
Mo	ug/L	81.1-118	11-58	81.1	113
Na	mg/L	19.2-68	1.8-7.1	19.2	14.3
Ni	ug/L	<3-<5	<1	<3	<10
Pb	ug/L	0.4-0.6	<0.05-0.1	0.4	<2
Zn	ug/L	<5-10	3-15	<5	<5

Note: "<" indicates concentration below the detection limit indicated.

¹Type I: Leachate from the first leaching step (and each subsequent leaching step thereafter) was used to sequentially leach five fresh solid samples. In theory, this type of leach tests could be considered complete when leachate concentrations of the constituents no longer increased. Leachate results for these tests constitute the "A" series, and are labeled A1, A2, A3, A4 and A5.

²Type II: A single solids sample was subjected to four consecutive leaches, each with a fresh lixiviant. This type of test could be considered complete when the leachate no longer contained concentrations of the constituent of interest above a pre-determined threshold.

Table 12: Pre- and Post-Kinetic Test Analyses on Cemented Paste Tailings from Unnamed Mine

(from Verburg et al., 2000)

	Pre-test	Post-test			
		crushed exposed	crushed submerged	intact exposed	intact submerged
Acid-Base Accounting					
Residual sulphur (%)	-	4.9	5.1	5.0	6.4
Pyritic sulphur (%)	36.4 ⁽¹⁾	28.7	30.2	27.0	28.7
Sulphate sulphur (%)	<0.7 ⁽²⁾	0.82	0.19	2.19	0.65
Total sulphur (%)	33.1	34.5	35.4	34.2	35.8
AP (kg CaCO ₃ /tonne) ⁽³⁾	1,138	897	944	844	897
NP (kg CaCO ₃ /tonne)	45	<0.1	18	<0.1	19
NP/AP	0.04	<0.0001	0.02	<0.0001	0.02
Mineralogy (%)					
Pyrite	67	55	67	48	50
Quartz	18	31	25	33	34
Gypsum		<5		10	
Calcite	4		<3		<3
Galena	1				
Marcasite					<3
Chalcopyrite	<3				<3
Chalcocite		<2			
Jarosite	<5	5		5	
Mica/illite	2				
Feldspar	3				
Geotechnical					
Moisture (%)	18.0	-	-	19.0	19.0
Permeability (cm/sec)	9.2x10 ⁻⁷	-	-	2.0x10 ⁻⁵	1.1x10 ⁻⁶

Notes:

(1) from iron content.

(2) from assumption that all calcite occurs as calcite and gypsum. This assumption likely results in an overestimate of the sulphur content as other calcium-bearing cement phases are not accounted for.

(3) from pyrite sulphur.

Table 13: Summary of Kinetic Testing on Cemented Paste Tailings from Unnamed Mine

(from Verburg et al., 2000)

Parameter	crushed exposed	crushed submerged	intact exposed	intact submerged
	Average concentrations (mg/L)			
Alkalinity	2.5	41.5	2.5	35.1
Sulphate	2,806	477	2,703	168
Iron (2+)	273	0.08	539	0.07
Total iron	302	0.04	651	0.05
Calcium	299	218	12.8	84.8
	Average mass-based release rates from week 20 through week 30 (mg/kg/week)			
Alkalinity	2.0	43.6	2.2	39.0
Sulphate	2,292	501	2,307	187
Iron (2+)	221	0.08	460	0.08
Total iron	244	0.05	555	0.06
Calcium	246	229	11.1	94.2

Table 14: Results from Gas Sampling of Eskay Creek Mine Backfilled Stopes

(from Barrick Gold Corp., 2002)

Sampling Interval Length (m)	Contact Sampled	O ₂ (%)	CO ₂ (ppm)
9.70	Both	17.9	0
5.20	Backfill only	19.0	0
3.90	Hangingwall	20.6	100
7.11	Footwall	20.2	0

FIGURES

Figure 1: Flooded Underground Mine

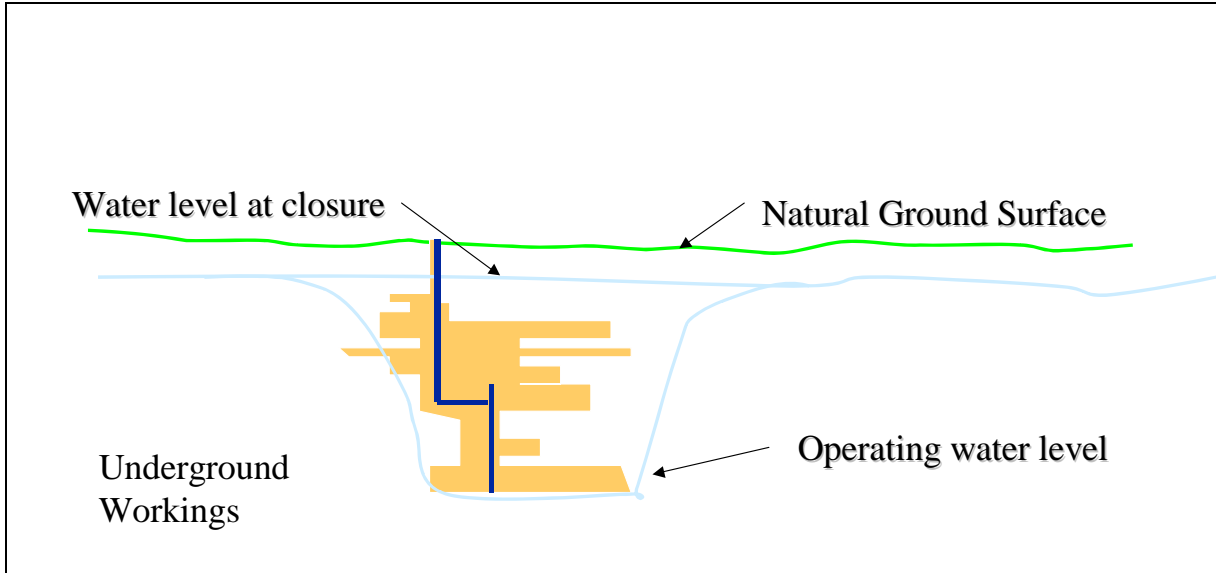


Figure 2: Sidehill Underground Mine

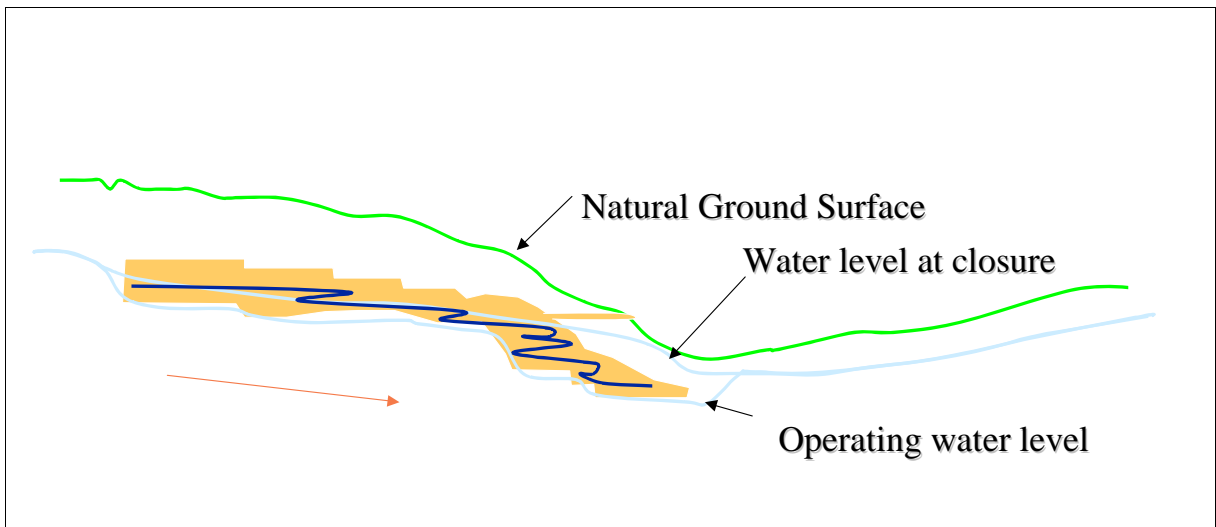
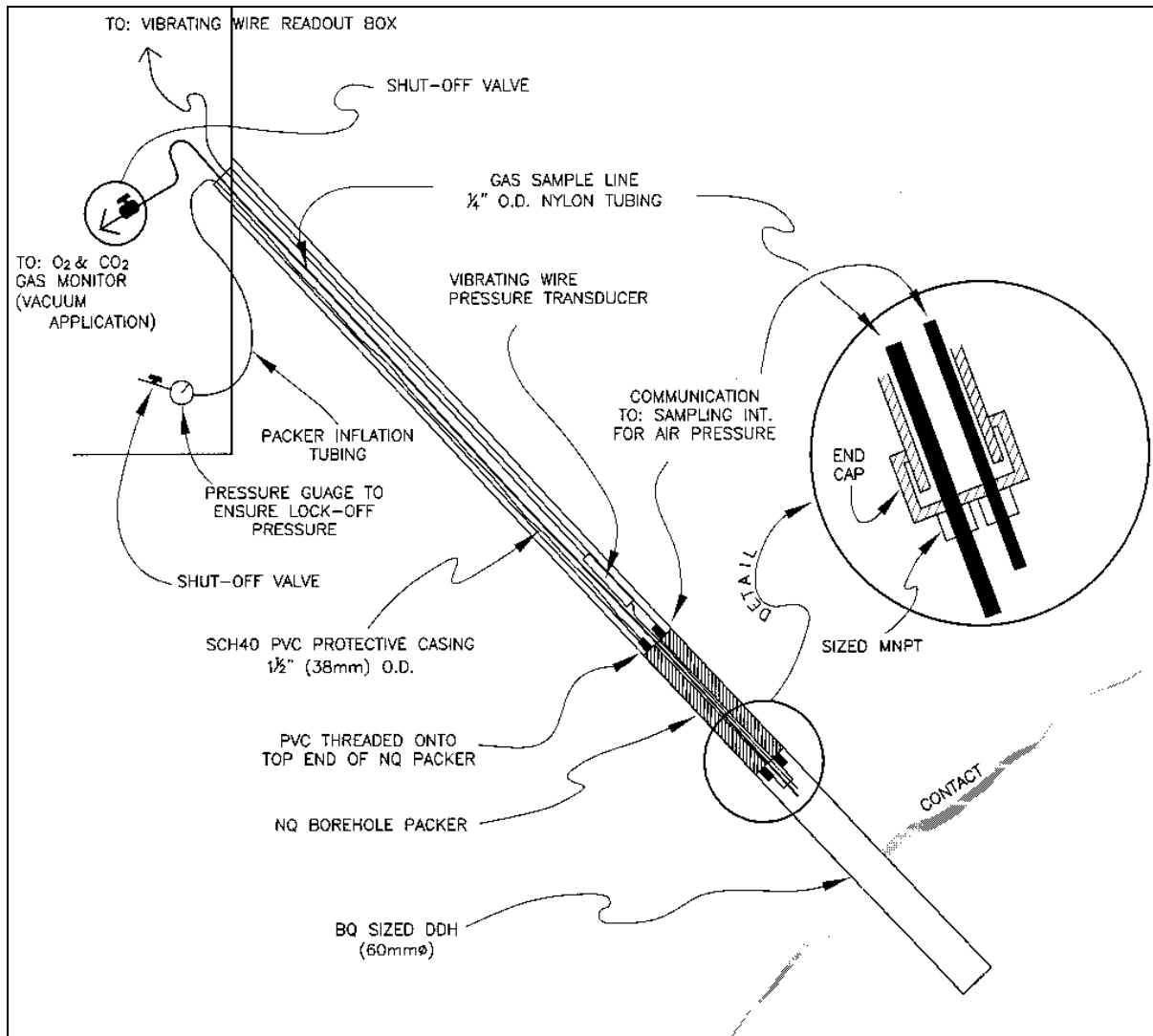


Figure 3: Gas Sampling in Eskay Creek Mine Backfilled Stopes



From Barrick Gold Corp, 2002.